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THESIS

AN INVESTIGATION OF COMMERCIAL OFF-THE-SHELF WIRELESS IN SUPPORT OF COMPLEX HUMANITARIAN DISASTER OPERATIONS IN THE ARGENTINE ARMY

by

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September 2012

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13. ABSTRACT (maximum 200 words)

Since the beginning of this century, the Argentine Army has used Commercial Off-The-Shelf (COTS) wireless products, equipment, and communication systems to support Humanitarian Assistance and Disaster Relief (HA/DR) operations.

The participation of Military, Governmental, and Non-Governmental Organizations in these activities requires more wireless coverage area. These communication systems are an integration of several subsystems that provide an initial Hastily Formed Network (HFN), but they did not provide enough coverage area to support Command and Control centers from different organizations.

This thesis explore different solutions to address the lack of coverage area of the current wireless systems, analyzing new COTS technologies that could be applied to the Argentine Military HFN Centers to satisfy the new emerging requirements of HA/DR operations. This research is focused on "Wireless Subsystems," and gather data from actual HA/DR experiments and exercises organized by NPS. The experiments provide analytic data from the latest generation equipment which are being tested at the NPS HFN center. The thesis determines the benefits that the applicability of different wireless subsystem would provide to support HA/DR operations in an Argentine environment based on the information gathered during field exercises and experiments.

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LIST OF ACRONYMS AND ABREVIATIONS

2G	Second Generation
3G	Third Generation
3G	Fourth Generation
AA	Argentine Army
AMPS	Advance Mobile Phone Service
AMSP	Andrew Molera State Park
AP	Access Point
APCO	Association of Public Safety Communication Officers International
BGAN	Broadband Global Access Network
BSS	Basic Service Set
CDMA	Code Division Multiple Access
CHSC	California Homeland Security Consortium
CMO	Civil-Military Operations
COTS	Commercial Off-The-Shelf
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DS	Distribution System
DSM	Distribution System Medium
DSSS	Direct Sequence Spread Spectrum
EDGE	Enhanced Data-rates for Global Evolution
EOC	Emergency Operation Center
ESS	Extended Service Set

FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum
FTX	Field Training Exercise
GPRS	Global Packet Radio Service
GSM	Global System for Mobile Communication
GUI	Graphic User Interface
HA/DR	Humanitarian Assistance/ Disaster Relief
HELP	Humanitarian Expeditionary Logistic Program
HFDR	High Frequency Doppler RADAR
HFN	Hastily Formed Networks
HING	Hawaiian Army National Guard
ICT	Information and Communication Technology
IDU	In Door Unit
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IPC3	Independently Powered Command/Control/Communication Program
ISDN	Integrated Services Digital Network
ISI	Inter-symbol Interference
ISP	Internet Service Provider
ITACS	Information Technology and Communication Services
ITM-2000	International Telecommunication Mobile 2000
ITM-A	International Telecommunication Mobile Advance
ITU-r	International Telecommunication Union - Radio

JCTD	Joint Capability Technology Demonstration
LAN	Local Area Network
LLC	Logical Link Control
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad Hoc Networking
MARCIMS	Marine Civil Information Management System
MARFORPAC	Marine Corps Forces Pacific
MCTC	Mobile Communication Trunking System
MEC	MARFORPAC Experimentation Center
MONAX	Mobile Network Access
NGO(s)	Non-Governmental Organization
NLOS	Non-Line-of Sight
NPS	Naval Postgraduate School
PHY	Physical Layer
PMP	Point-To-Multipoint
POTS	Post Office Telephone Service
PTP	Point-To –Point
ODU	Out Door Unit
OFDM	Orthogonal Frequency-division Multiplexing
PoE	Power over Ethernet
QoS	Quality of Service
RF	Radio Frequency

RSSI	Received Signal Strength Indicator
SINADR	Signal, Noise and Distortion Ratio
SNR	Signal-to-Noise Ratio
STA	Station
UAS	Unmanned Aircraft System
UN	United Nations
TD-CDMA	Time Division - Code Division Multiple Access
TDMA	Time Division Multiple Access
VSAT	Very Small Aperture Terminal
WAVE	Wireless Access in Vehicular Environments
W-CDMA	Wideband Code Multiple Access
WDS	Wireless Distribution System
WECA	Wireless Ethernet Compatibility Alliance
WIFI	Wireless Fidelity
WIMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

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I. INTRODUCTION

A. COTS AND HFN

Since the beginning of this century, the Argentine Army has used Commercial Off-the-Shelf (COTS) products, equipment, and communication systems to support Disaster Relief Efforts during emergencies and natural disasters. COTS equipment not only increased the interoperability of the Army communication systems with those of other governmental and non-governmental organizations and institutions, it also improved its communication capabilities.

In recent decades, the technology life cycles of high-tech devices have declined tremendously; they are getting shorter and technology Upgrade/Replacement is required more frequently (Voessner & Lichtenegger, 2011). COTS communication devices are affordable and provide quick solutions for this dilemma. The Information and Communication Technology (ICT) military industry is being overcome by available commercial systems, and the trend is that the military is using more COTS equipment.

In 2001, the Argentine Army Communication Directorate delivered the first analog prototype of the Mobile Communication Trunking Center (MCTC). In 2007, a second model called Mobile Communication Trunking Center 2 (MCTC 2) was developed and delivered—improving original MCTC capabilities and services through the use of newly available digital equipment. These systems are still providing Hastily Formed Networks to crisis centers in Humanitarian Assistance and Disaster Relief (HA/DR) operations.

B. PROBLEM STATEMENT

Even though both systems (MCTC-1 and MCTC-2) are still in service, the problem is that they are not delivering sufficient coverage area to support Humanitarian Assistance and Disaster Relief (HA/DR) Operations. In fact, in every new natural disaster more and more military, governmental, and non-governmental organizations (NGO) are participating in these activities, demanding more coverage area and throughput. MCTC-1 and MCTC-2 are an integration of several subsystems that provide an initial Hastily

Formed Network (HFN) in a disaster area, but they do not provide enough coverage area to support Command and Control centers from different organizations. The increasing demand of communication services has made these systems insufficient. The Argentine Army Communication Directorate is continuously searching for new equipment or devices that can improve the performance of Hastily Formed Networks to support HA/DR operations in Argentina and overseas (e.g., Haiti).

C.   PURPOSE STATEMENT

The purpose of this research is to find an adequate potential solution for the lack of coverage area of the "MCTC Models," analyzing new COTS technologies that could be applied to the Argentine Military Hastily Formed Network Centers to satisfy the new emerging requirements of Humanitarian Assistance and Disaster Recovery operations. This research is focused on "Wireless Subsystems."

D.   RESEARCH QUESTIONS

1.   How will new WiFi COTS Wireless technologies provide larger coverage areas than recent wireless systems?

2.   How will new WiMAX COTS Wireless technologies provide more bandwidth than recent wireless systems?

3.   How will new BGAN COTS Satellite equipment provide more throughput than recent satellite systems?

4.   How will new cellular systems provide more coverage area and throughput than recent trunking systems?

E.   BENEFITS

The analytical study of COTS systems will provide a better understanding, and an evaluation of them will provide solid information to support acquisition decision making. Budget constraints are more acute and communication services are more expensive nowadays, and this thesis will try to find a balance between services and cost.

This thesis will provide broad recommendations applicable to any governmental organization that operates in HA/DR missions where communication systems are

available. Even though the study is oriented to address the specific requirements of the Argentine Army, the communication support of HA/DR operations is a worldwide matter.

Even though this thesis has a limited time for evaluation and validation (because it analyzes specific systems that are currently available), the structure of this thesis will be applicable in a few years—when new systems are available for evaluation. It will also be a basis for future research for comparison, and for evaluation of the evolution of COTS communication systems in support of HA/DR operations.

Finally, the thesis will provide some recommendations about how to improve communication systems for better support of multi-agency HA/DR operations.

F.   METHODOLOGY

The methodologies used in this thesis are the following:

- Review of articles, after action reports, and statistics from major disasters in the last 20 years in Argentina and in the world with the purpose of identifying the practices and lessons learned as they relate to communication capabilities during the early stages of a disaster.

- Study and analyze the new different technologies in use by the Naval Postgraduate School-Hastily Formed Network Center (NPS-HFN) to provide communication support to Humanitarian Assistance/Disaster Relief operations.

- Participate in various NPS HFN Center field exercises and experiments in support of the NPS Independently Powered Command/ Control/Communication Program (IPC3) to acquire data from real-world scenarios. The experiments included research by faculty and students from NPS, as well as the end-user customer for these technologies, which is the California Homeland Security Consortium (CHSC), members from throughout the County of Monterey—specifically the Monterey County Office of Emergency Services.

- Participate and develop field experiments to obtain additional information about HFN wireless technologies in support of HA/DR operations.

- Analyze the behavior of different wireless technologies in real-world scenarios to formulate conclusions about their applicability to Argentine Army HFN centers.

G. THESIS STRUCTURE

1. Chapter I: Introduction

This chapter gives a general outline of the problem with a description of the research motivation, and the research questions that will be answered.

2. Chapter II: Humanitarian Assistance/Disaster Relief

This chapter describes the characteristics of Humanitarian Assistance and Disaster Relief (HA/DR) operations around the world and in Argentina, specifically. Then, it describes the different approaches to supporting these operations taken by the Hastily Formed Network (HFN) center at NPS and the Argentine Army.

3. Chapter III: Technology Overview and Research Design

This chapter analyzes the different new Wireless systems that can improve Argentine's HFN. It describes in detail the new technologies and specific equipment that are used in field experiments and exercises. In addition, it describes the general research design for these wireless solutions.

4. Chapter IV: Experiments and Exercises

This chapter describes and analyzes the performance of different wireless solutions during the field experiments and exercises in which the NPS HFN center participated, and proposes the potential use of these in Argentine HFN centers.

5. Chapter V: Conclusion

This chapter summarizes the key findings of this thesis and expresses recommendations. It also proposes future research in this topic area.

II. HUMANITARIAN ASSISTANCE / DISASTER RELIEF

In this chapter, the author will describe characteristics of Humanitarian Assistance and Disaster Relief (HA/DR) operations around the world and in Argentina, specifically. Then, he will describe the different approaches taken by the Hastily Formed Network (HFN) center at NPS and the Argentine Army to support HA/DR operations.

A. HUMANITARIAN ASSISTANCE / DISASTER RELIEF

1. Around the World

The international community has responded to many natural and human disasters over time, from earthquakes and floods to famine and war. Several national and international agencies have procedures in place to facilitate the collection and delivery of aid to stricken areas (Joint Tactics, Techniques, and Procedures for Foreign Humanitarian Assistance, 2001).

The terrorist attack on the World Trade Center on September 11, 2001, and several major natural disasters—like the earthquake and tsunami in Southeast Asia on December 26, 2004—have demonstrated to the entire world the weakness of communications systems in response to these kinds of events. Investigations into radio communication systems during the September 11th attacks revealed that communication systems and protocols that distinguished each department were hampered by the lack of interoperability, damaged or incapacitated by failed network infrastructure during the attack, and overwhelmed by simultaneous communications between superiors and subordinates.

In the wake of a large disaster, it is often difficult to accurately assess aid allocation due to gaps in the available information (Maxwell, 2003). In some of the areas most devastated by tsunamis, electricity and telephones are not available. In these areas, amateur radio remained the only connection to the rest of the world. In some instances, communication can be further limited to use of Morse code in order to preserve the power of car batteries used to operate the radios.

Without a communication infrastructure, it is also difficult to coordinate responders, which include a wide array of personnel from national disaster management organizations, national government agencies, local government units, military-civil defense forces, United Nations agencies, international military and civil defense forces, international aid agencies, international NGOs, and private volunteers.

The high frequency of major global disasters in the past decade (Hurricane Katrina, the Haitian Earthquake, the Chilean Earthquake) has created a growing focus on the international community's response to severe challenges associated with effectively communicating, coordinating, and interoperating in a multi-national/multi-agency disaster relief operation. Communications have been identified as a key piece in the coordination of responders involved in HA/DR operations (Provost, 2011).

2. In Argentina

As in any other country around the world, Argentina has to deal with man-made and natural disasters. On March 17, 1992, at 2:42 pm (UTC-3), a pickup truck driven by a suicide bomber and loaded with explosives smashed into the front of the Israeli Embassy (located on the corner of Arroyo St. and Suipacha St.) and detonated. The embassy, a Catholic church, and a nearby school building were destroyed. Four Israelis died, but most of the victims were Argentine civilians, many of them children (Bergman, 2008).

The last major man-made disaster was the AMIA bombing attack on the Asociación Mutual Israelita Argentina (AMIA) building in Buenos Aires on July 18, 1994, which killed 85 people and injured hundreds. It was Argentina's deadliest terrorist bombing ever. Argentina is home to a Jewish community of 200,000, the largest in Latin America (BBC, 2006). Both of these facts have introduced Argentina and the region to an era of HA/DR operations that stem from man-made disasters.

Argentina also has many natural threats to deal with—such as earthquakes, flooding, fires, avalanches, tornadoes and volcanoes eruptioning. For example, the San Justo Tornado struck San Justo, a town in the province of Santa Fe, Argentina, on January 10, 1973. Sixty-five people were reported dead and 350 were reported injured. It cut a 300-yard wide swath through the town. More than 300 homes were destroyed or

damaged. Some homes were said to have vanished with little or no trace. This indicates that the tornado could have been an F5 on the Fujita Scale. The tornado was the most dangerous ever reported in Argentina and was responsible for great economic loss (Mino, 1973).

In April 2003, Santa Fe, the fifth-most populated city in Argentina (~370,000 inhabitants) and surrounded by rivers, suffered a flooding described as the worst since the city was founded in 1573. About 100,000 people had to be evacuated, 24 people died, and 28,000 houses were damaged or destroyed (BBC, Argentina Flood toll rises, 2003). The flooding was the worst catastrophe in the history of Santa Fe province.

Argentina also has large earthquake areas along the Los Andes range. The 1944 San Juan earthquake took place in the province of San Juan, in the center-west area of Argentina, a region highly prone to seismic events. This moderate to strong earthquake (estimated moment magnitudes range from 6.7 to 7.8) destroyed a large part of San Juan, the provincial capital, and killed 10,000 of its inhabitants (10% of its population at the time). One third of the province population became homeless. It is acknowledged as the worst natural disaster in Argentine history (Healey, 2002). On November, 23, 1977, another earthquake took place in San Juan province. It is recorded as a major seismic movement that took place in Argentina and measured magnitude 7.4 on the Richter scale. This earthquake caused fatalities and severe damage to buildings throughout the province, especially in the city of Caucete, where 65 people died. It also caused slight damage in the north of the Greater Mendoza metropolitan area.

According to Bloomberg.com's Global Facility for Disaster Reduction and Recovery, 2007 Annual Report, Argentina ranks 27th out of 50 for natural disaster hotspots. Only 1.8% of the total area is considered at risk, but 54.7% of the country's population lives in that risk area. The main disasters people have faced are flooding and earthquakes. In the last ten years, according to the international emergency disaster database EMDAT, over 700,000 people were affected by floods, which caused over USD $2,000,000 in damages.

Figure 1 shows the statistical data related to occurrence reports from disasters that have occurred between 1980 and 2010 in Argentina (PreventionWeb, 2011).
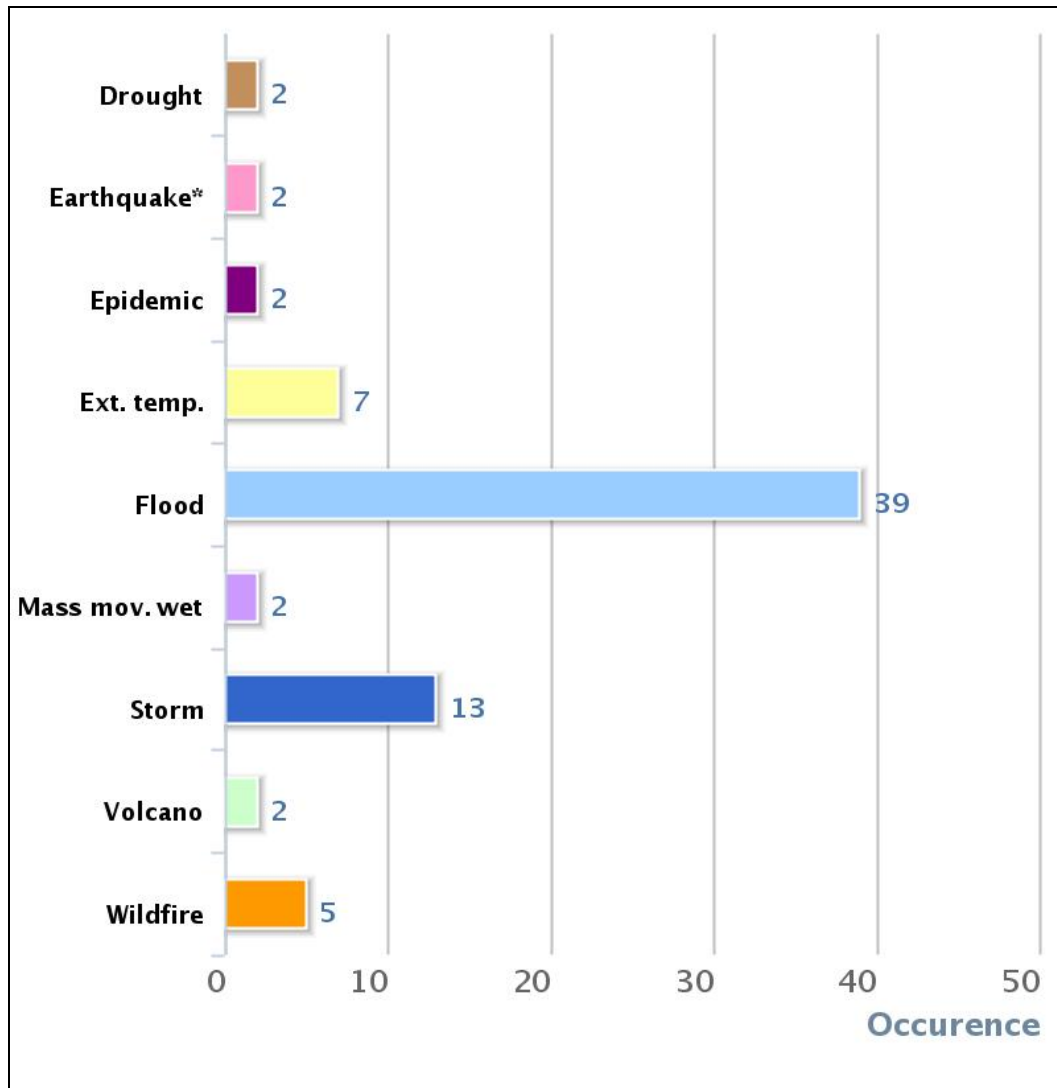
* Including tsunami.

Figure 1.   Occurrence reported disasters in Argentina 1980–2010 (From PreventionWeb, 2011)

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B. HASTILY FORMED NETWORKS

1. United States Department of Defense + Naval Postgraduate School

The Department of Defense (DoD) and the Naval Postgraduate School (NPS) coined the term Hastily Formed Networks (HFN) to describe the portable IP-based networks which are deployed in the immediate aftermath of a disaster when normal communication infrastructure has been degraded or destroyed. The IT communication infrastructure created by HFN can provide valuable basic communications (voice/video/data) until pre-disaster infrastructure (if any) can be restored.

Early implementations of these ad hoc disaster networks were slow, primitive, and unreliable. In the past, the equipment required to implement HFN was expensive, cumbersome, and in—many cases—only available to the military or large corporations. The advent of highly reliable and affordable Commercial Off-The-Shelf (COTS) equipment allows for the implementation of successful HFN in support of HA/DR operations.

Since 2004, the NPS HFN Center led by Brian Steckler (and triggered by the December 26, 2004 Southeast Asia tsunami) has researched this topic. This research group is focusing on the use of wireless technologies, such as Satellite Communication Systems, Mesh Wireless Fidelity (WiFi), and Worldwide Interoperability for Microwave Access (WIMAX). This group has increased its experience and capability by researching other disasters, such as Hurricane Katrina, the Haitian Earthquake, and many exercises such as Strong Angel and Urban Shield. The NPS HFN Center has developed extensive research on networks in extreme environments.

As a consequence of globalization, more multinational agencies are eager to participate in the support of HA/DR operations, but the lack of a communication system able to coordinate and integrate efforts is still the main obstacle to overcome. HFNs that enable communication infrastructure are, therefore, essential for a rapid and effective HA/DR response.

2. The Argentine Army

Since its creation in 1810, the Argentine Army (AA) has been supporting HA/DR operations as one of its main missions. Historically, the AA has been providing security, transportation, shelter, food and medical assistance to people affected by disasters. It has used its organic communication system to command these operations without integrating with other governmental or non-governmental organization (NGO). The only point of contact with an NGO was with the Radio Amateur Association (Ham Radio) and with the Radio Amateur Clubs that were always eager to collaborate in HA/DR operations.

At the end of the last century, the AA Communication Directorate began to develop new modern communication systems with COTS equipment in order to increase its capabilities for supporting the increasing demand for data information sharing in military operations. These projects were developed under the concept of dual use, meaning these systems could be used in both military and nonmilitary operations. The first such development was the Mobile Communication Trunking Center (MCTC), which has been in service since 2001.

3. Mobile Communication Trunking Center

In September 2001, after almost a year of design and development, the AA Communication Directorate delivered the first prototype of the MCTC for City Bell, Buenos Aires province. This system was designed to support communication and information transmission to a Command Center through the transmission, routing, and distribution of voice, data, and video—constituting an extension of the force's field of fixed communications and computer networks.
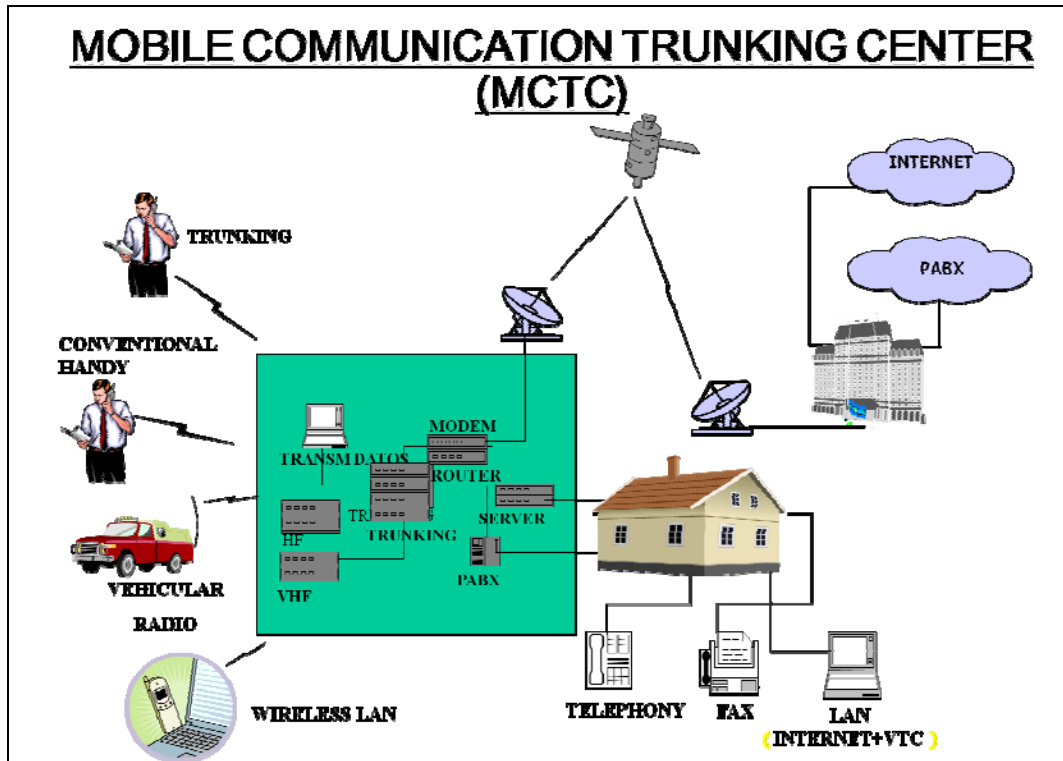
Figure 2.   Mobile Communication Trunking Center

This was the first in-house development of a communication system using COTS equipment designed by Argentine military engineers. This prototype has the following subsystems:

- Hybrid PABX (wired telephone subsystem)

- 256 Mbps Satellite link

- Trunking (Analog automatic two way radio) site

- Analog VHF repeater

- HF and military VHF band radios

- Wired LAN (20 ports)

- Wireless LAN Access Point

- Net and message Servers

- Gas generator plus Uninterrupted Power Supply (UPS)

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The MCTC represents the beginning of a new era for Argentine military communications because of the use of COTS, home-made, and dual-purpose development. All components (except for the military VHF band radios) are affordable and easily replaceable COTS equipment. MCTC introduced the use of a commercial Ku band satellite link. There was complete knowledge transference from the commercial to the military sector. However, the more important consequence that it brought was its crucially reliable performance in almost all HA/DR operations. This reliability was required by other government agencies to support all kinds of complex disaster relief activities, such as flooding, epidemic, fires, and earthquakes.

Figure 3.   Different views of MCTC

Given the low cellular phone coverage in general throughout Argentina and the common failure of cellular service that often occurs during disasters, the MCTC could provide reasonable voice communication support to HA/DR operations with its analog

Trunking system, but a very small WiFi (IEEE 802.11b) coverage area (given its singular access point at the top of a 30-foot mast).

A new architecture communication system was introduced using this new development. All traditional schemas were slightly adapted as shown in Figure 4:
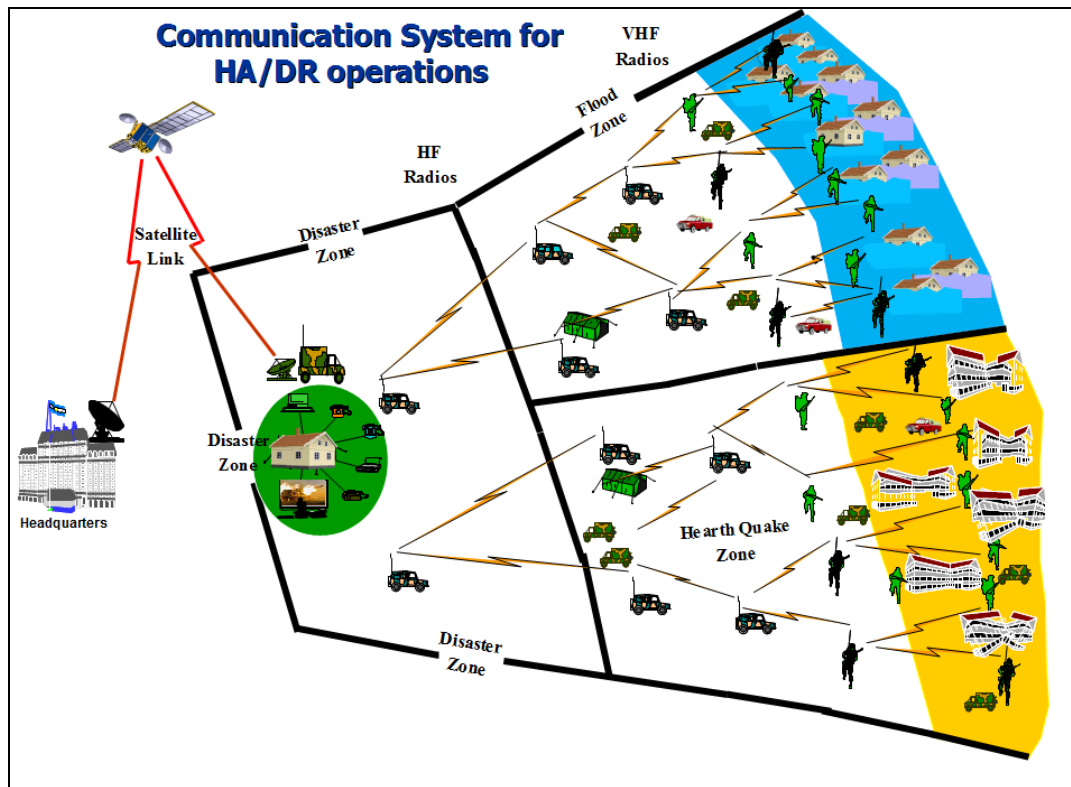
Figure 4.   Communication System for HA/DR operations with MCTC.

4.   Mobile Communication Trunking Center 2

In 2006, a second prototype called Mobile Communication Trunking Center-2 (MCTC-2) was developed and delivered by the AA Communication Directorate. Following the same concept, this new prototype meets the goals of greater security in its communication systems with the use of digital equipment. In this case, a Motorola APCO P 25 standard is used for digital radio communications. The main feature of this prototype is how it enables the federal, provincial, and local public safety agencies to communicate with other agencies and with mutual aid response teams in emergencies.

This second digital version of MCTC includes more wireless data capabilities. In addition to one Access Point IEEE 802.11b (11 Mbps, 2.4 GHz) an omni-directional antenna and Power over Ethernet (POE), it includes two Access Points IEEE 802.11a (5.725–5.850GHz) with integrated antennas to perform a point-to point wireless bridge between two Local Area Network (LAN).

Figure 5 shows the architecture of the solution:
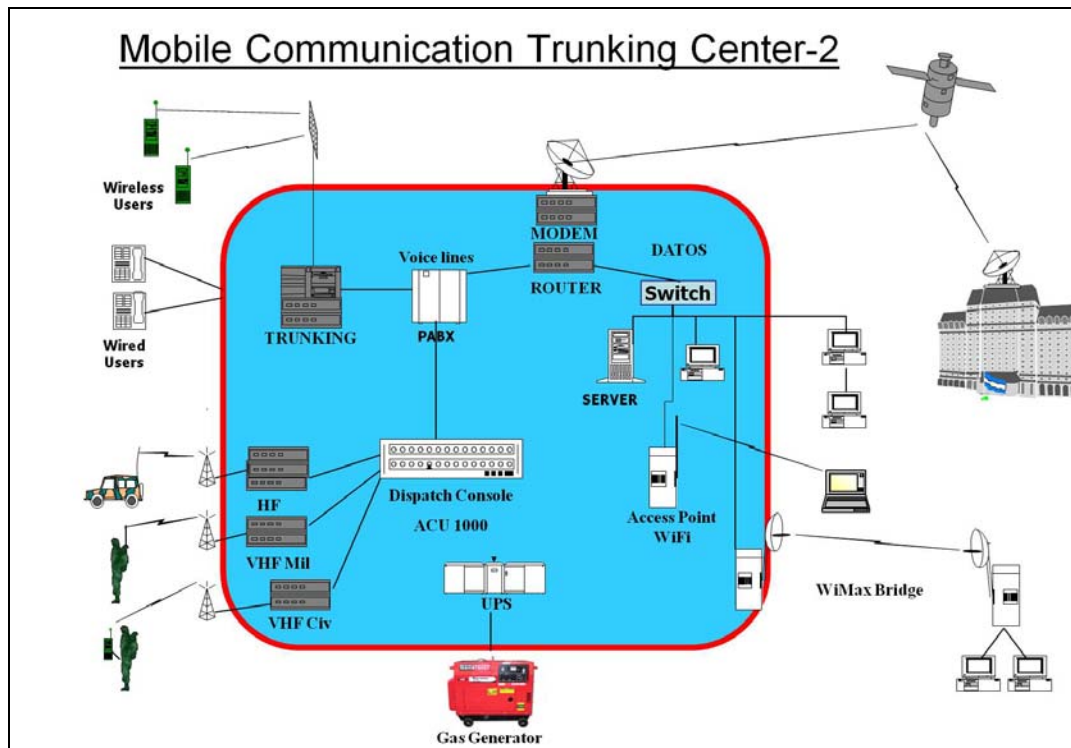
Figure 5.   MCTC 2 Block diagram

The main differences between this prototype and the first one are:

- Digital trunking APCO P 25 radio system
- ACU 1000 dispatch console
- WiMax Bridge IEEE 802.16
- Motorized satellite antenna system (1.2 m)
- Smaller and more efficient gas generator

Figure 6.   Mobile Communication Trunking Center-2

MCTC-2 represents an important improvement in communication support to HA/DR operations from the point of view of interoperability, security, and readiness. The new wireless bridge equipment also provides the capability to provide data communication to another command center located up to approximately 5 kilometers away.

Since this development, new COTS technologies have been made available for introduction to military HA/DR operations. They could significantly improve the interoperability and support of the Argentine forces and other agencies that participate in these operations.

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III. TECHNOLOGY OVERVIEW AND RESEARCH DESIGN

In this chapter, the author details the new technologies and specific equipment that will be used in field experiments. In addition, he describes the general research design for these solutions.

A. WI-MAX IEEE 802.16

1. Orthogonal Frequency-Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) is a special form of multi-carrier modulation patented in 1970. OFDM can be simply defined as a form of multicarrier modulation where its carrier spacing is carefully selected so that each subcarrier is orthogonal to the other subcarriers. As is well known, orthogonal signals can be separated at the receiver by correlation techniques; hence, inter-symbol interference (ISI) among channels can be eliminated. It is particularly suited for transmission over a dispersive and multipath channel. Most conventional modulation techniques are sensitive to inter-symbol interference unless the channel symbol rate is small compared to the delay spread of the channel. OFDM is significantly less sensitive to inter-symbol interference, because a special set of signals is used to build the composite transmitted signal. The basic idea is that each bit occupies a frequency-time window which ensures little or no distortion of the waveform. In practice, it means that bits are transmitted in parallel over a number of frequency-nonselective channels.

Figure7 shows the signal spectrum of an OFDM signal, which consists of the spectra of many bits in parallel. Rectangular pulses in the time domain produce *sinc*-functions in the frequency domain (Fourier Transform). The signal represented above is the signal spectrum as transmitted, and the one below represents the signal as received over a dispersive time-invariant channel. Hence, although some of the carriers are degraded by multipath fading, the majority of the carriers should still be adequately received. OFDM can effectively randomize burst errors caused by Rayleigh fading. So, instead of several adjacent symbols being completely destroyed, many symbols are only slightly distorted. Because an entire channel bandwidth is divided into many narrow sub-

bands, the frequency response over each individual sub-band is relatively flat. This allows the precise reconstruction of the majority of the symbols, even without forward error correction (FEC).
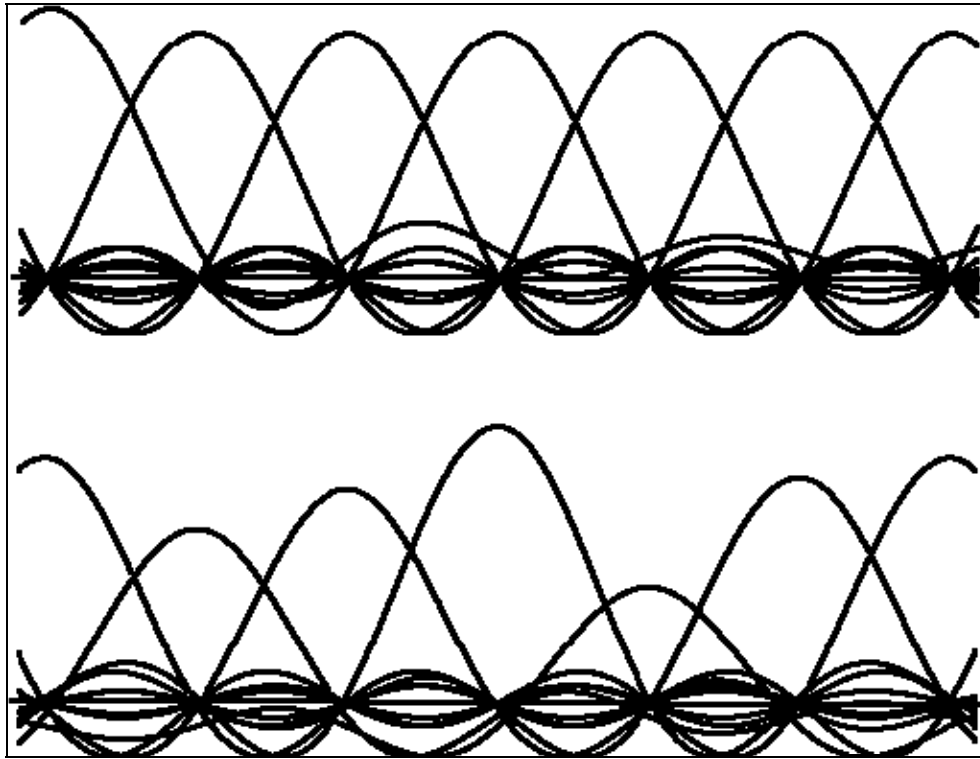
Figure 7.   OFDM Wave form (From Stallings, 2005)

2.   WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) is a point to multipoint broadband wireless bridge system that has been developed for use as a broadband wireless access device for fixed and mobile stations and can provide a wireless alternative for last-mile broadband access in the 2 GHz-66 GHz frequency range (Beasley & Miller, 2008).

WiMAX Broadband wireless access for fixed stations can be up to 30 miles (48 Km), whereas 802.11 WiFi mobile access is 3 to 10 miles (5 to 16 Km). Internationally, the WiMAX frequency standard is 3.5 GHz, unlicensed 5.8 GHz and licensed 2.5 GHz. There are also investigations into adapting WiMAX for use in the 700

MHz frequency range with the advantage of better tree signal penetration, but at less bandwidth (Beasley & Miller, 2008).

WiMAX uses OFDM as its signaling format in standard IEEE 802.16a because of its improved NLOS (non-line-of-sight) characteristic in the 2 GHz to 11 GHz frequency range. OFDM systems use multiple frequencies to transport data, which helps to minimize multipath interference problems. WiMAX also provides flexible channel sizes (e.g., 3.5 MHz, 5 MHz, and 10 MHz) which provide adaptability to standards worldwide and help to ensure that a minimum data transfer rate is being supported. In addition, WiMAX operates in a collision-free environment that improves channel throughput.

3.   Redline AN-80i System Point-To-Point

During the different experiments, the Hastily Formed Network (HFN) center provides AN-80i Point-To-Point (PTP) systems from Redline Communications Inc., Canada. The AN-80i radio platform can be software configured to create either PTP communication links between network locations or high speed point-to-multipoint (PMP) access links between business users and their corporate networks. We are using the PTP configuration that can provide a throughput of 108 Mbps at 40 MHz bandwidth with a 1 ms latency, 50 miles (80 Km) maximum range, single polarization external antennas, 5.8 GHz FCC/IC band (5.725 – 5.850 GHz), 25 dBm output power, configurable channel size (3.5/5/7/10/14/20/28/40 MHz), and low power consumption (13W). In addition, the communication data channel can be encrypted using AES-128/256 with FIPS 140–2 certification which implies a high security capability (Redline Communications, 2011).

Figure 8.   Redline AN-80i (From Redline, 2011)

The AN-80i PTP System provides many useful features for quick and easy configuration and installation. The Graphic User Interface (GUI) provides visual access to the whole device configuration and makes required software upgrades easy to accomplish. Before first use, one specific manufacturer-provided Activation Key must be installed, enabling the features purchased for the device. The GUI also has a spectrum analyzer that provides actual information about spectrum availability. Checking channel availability is recommended before attempting to establish the PTP link, in order to avoid interference and to ensure use of a clear channel. Another feature provided by the GUI is an instantaneous signal level of the established link with Signal, Noise, and Distortion Ratio (SINADR) and Received Signal Strength Indicator (RSSI) values in real time that are very useful to antenna alignment and link performance improvement. In addition, and for the installation of quick antenna alignment, the AN-80i has an antenna alignment buzzer that provides an audible signal of the received signal strength (the stronger the signal, the faster the repetitions).
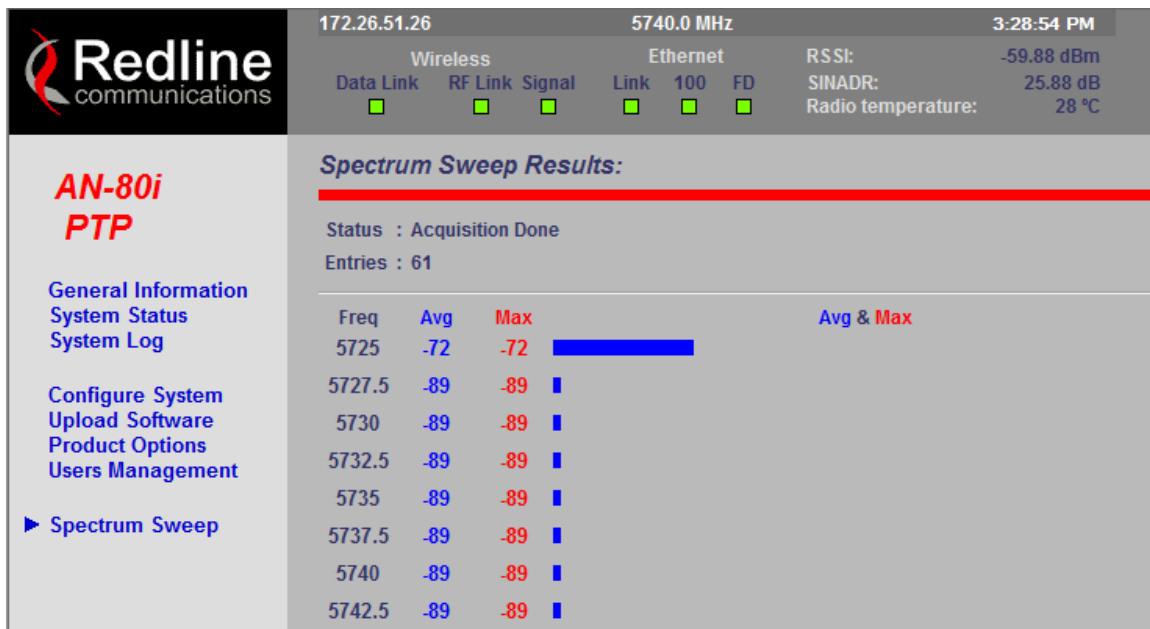
Figure 9.   Redline GUI interface – RSSI, SINADR and Spectrum Analyzer

The PoE unit complies with IEEE 802.3af PoE and can be energized with any 110/220/240 VAC 50/60 Hz power source. The maximum distance of the Cat 5 cable between the PoE unit and the radio is 300 ft (91 m). The radio unit weighs 4.5 lbs (2.0 Kg) without bracket or antenna.

During the exercises and experiments, we used directional, sector, and omni-directional antennas.

Directional antenna:

- Model: A2804MTFW, 2-foot panel type, angle 4.5°, polarization V/H, gain 28 dBi, Bandwidth 4.9 to 5.925 GHz, origin India.

Figure 10.   Redline A2804MTFW 2-foot panel antenna (From Redline, 2011)

- Model: A2209MTFW, 1-foot panel type, angle 9°, polarization V/H, gain 22 dBi, Bandwidth 5.15 to 5.875 GHz, origin India.
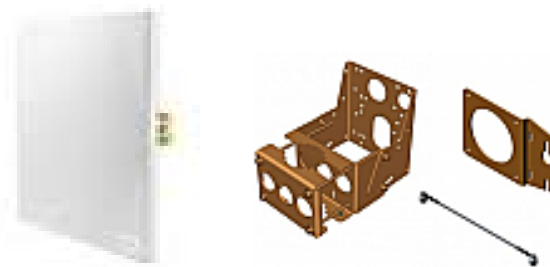
Figure 11.   Redline A2209MTFW 1-foot panel antenna and mounting kit (From Redline, 2011)

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Sector Antenna:

- Model SA58–120–16-WB: Vertical Polarized Sector Antenna: 120°, 16 dBi, 4.47 to 5.85 GHz.

The vertically polarized sector antenna systems made by Laird Technologies are constructed of UV stable ABS plastic radomes and die-cast aluminum brackets for long service life in the most demanding conditions. The antennas are DC grounded for lightning/ ESD protection. The super heavy duty bracket system is easy to install and adjust for up to 15° of down tilt. The single bracket system allows for easy deployment of multiple sectors on a single pole (Laird Technologies, 2011).
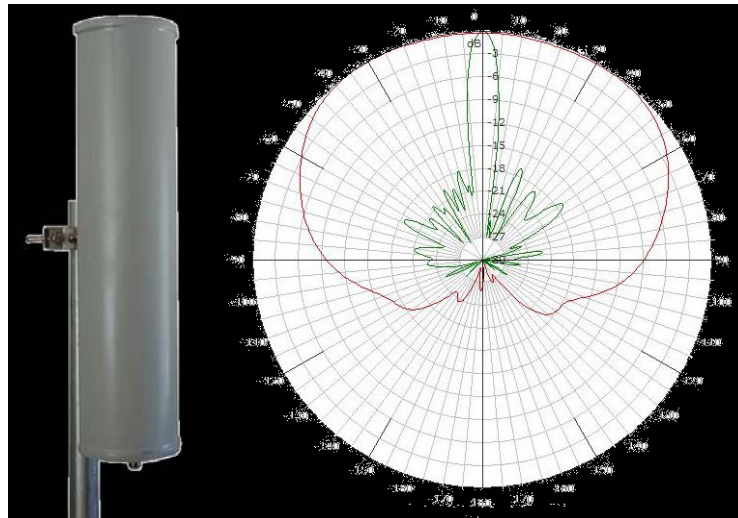
Figure 12.   Vertical Polarized Sector Antenna SA54=120–16-WB and antenna pattern (From Laird Technologies, 2011)

Omni-directional antennas:

- Model Comet SF-5818N-SR: 5.8 GHz Outdoor Omni-Directional V-Pol 9.1 dBi. Maker: Microcom Technologies, Inc.

Figure 13.   Omni-Directional antenna Comet SF-5818N-SR (From Microcom Technologies, 2005)

- Model Terrawave Solutions T58120O10006 12 dBi. 5.7 to 5.85 GHz. Maker: TESSCO Technologies Inc.

TerraWave's 12 dBi, fiberglass, omni-directional antenna is designed for 5.7–5.85 GHz wireless local area networks. It features a UV-stable, vented radome that provides ultimate sustainability against extreme weather conditions such as high temperature, strong winds, and rain. It can be mast or wall mounted (Terrawave, 2006).
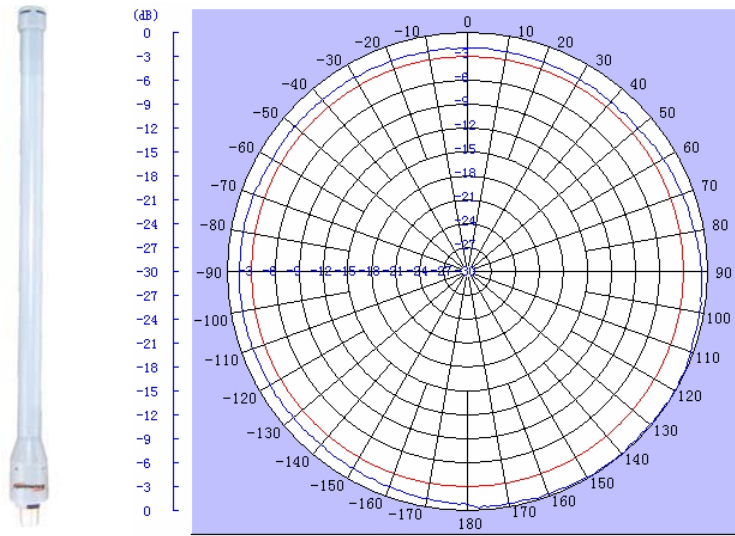
Figure 14.   Terrawave Solutions T58120O10006 antenna and horizontal antenna pattern (From Terrawave Solutions, 2006)

B.   WI-FI MESH IEEE 802.11S

1.   IEEE 802 Architecture Overview

The IEEE has standardized the protocol architecture for LANs, which encompasses both physical medium access control (MAC) and logical link control (LLC) layers through the IEEE 802 reference model. In 1990, the IEEE 802 committee formed the IEEE 802.11 working group to develop the most prominent specification for wireless LANs (WLAN). The initial interest was in developing a wireless LAN able to operate in the industrial, scientific, and medical band. Since that time, the demand for WLANs has exploded. Keeping pace with the demand, the IEEE 802.11 working group has issued an ever-expanding list of standards.

Standard	Date	Scope
IEEE 802.11	1997	Medium access control (MAC): One common MAC for WLAN applications
		Physical layer: Infrared at 1 and 2 Mbps
		Physical layer: 2.4 GHz FHSS at 1 and 2 Mbps
		Physical layer: 2.4 GHz DSSS at 1 and 2 Mbps
IEEE 802.11a	1999	Physical layer: 5 GHz OFDM at rates from 6 to 54 Mbps
IEEE 802.11b	1999	Physical layer: 2.4 GHz DSSS at 5.5 and 11 Mbps
IEEE 802.11c	2003	Bridge operation at 802.11 MAC layer
IEEE 802.11d	2001	Physical layer: Extend operation of 802.11 WLAN to new regulatory domains (countries)
IEEE 802.11e	2005	MAC: Enhance to improve quality of service (QOS) and enhance security mechanisms
IEEE 802.11f	2006	Recommended practices for multi-vendor, access-point interoperability
IEEE 802.11g	2003	Physical layer: Extend 802.11b to data rates > 20Mbps
IEEE 802.11h	2004	Physical/MAC: Enhance IEEE 802.11a to add indoor and outdoor channel selection and improve spectrum and transmit power management
IEEE 802.11i	2004	MAC: Enhance security and authentication mechanisms
IEEE 802.11j	2004	Physically Enhance IEEE 802.11a to conform to Japanese requirements
IEEE 802.11k	2008	Radio resource measurement enhancements to provide interface to higher layers for radio and network measurements
IEEE 802.11m	2007	Maintenance of IEEE 802.11 1999 standard with technical and editorial corrections
IEEE 802.11n	2009	Physical/MAC: Enhancements to enable higher throughputs
IEEE 802.11p	2010	IEEE 802.11 standard to add wireless access in vehicular environments (WAVE).
IEEE 802.11 r	2008	IEEE 802.11 standard to permit continuous connectivity aboard wireless devices in motion
IEEE 802.11s	2011	Mesh Networking

Table 1.   IEEE 802.11 standards (From IEEE, 2006)

The first 802.11 standard to gain broad industry acceptance was 802.11b. Although 802.11b products are all based on the same standard, there is always a concern whether products from different vendors will successfully inter-operate. To meet this concern, the Wireless Ethernet Compatibility Alliance (WECA), recently renamed the Wi-Fi Alliance, was formed in 1999 (Stallings, 2005). As of 2004, 802.11b products from over 120 vendors were certified.

At present, there are many new standards which are still in development, for example:

Standard	Date	Scope
IEEE 802.11af	Ongoing	TV Whitespace
IEEE 802.11ah	Ongoing	Sub 1 GHz
IEEE 802.11ai	Ongoing	Fast Initial Link Setup

Table 2.   IEEE 802.11 standards in process (From IEEE, 2012)

The classic IEEE 802.11 WLAN infrastructure is described in Figure 15. A station, or STA, is an 802.11 standard-compliant MAC and physical layer (PHY) implementation, and it constitutes the basic entity in an 802.11 network. The most elementary 802.11 network, or Basic Service Set (BSS), can be formed using two STAs. If one station provides integration service to another station, the former is referred to as an Access point (AP). An AP provides STAs access to the Distribution System (DS). The DS provides the services needed to communicate with devices outside the BSS and allows APs to unite multiple BBSs to form an Extended Service Set (ESS). Within the ESS, STAs can roam from one BSS to another. Today, Ethernet IEEE 802.3 standard usually provides the Distribution System Medium (DSM). The WLAN APs are typically "wired."
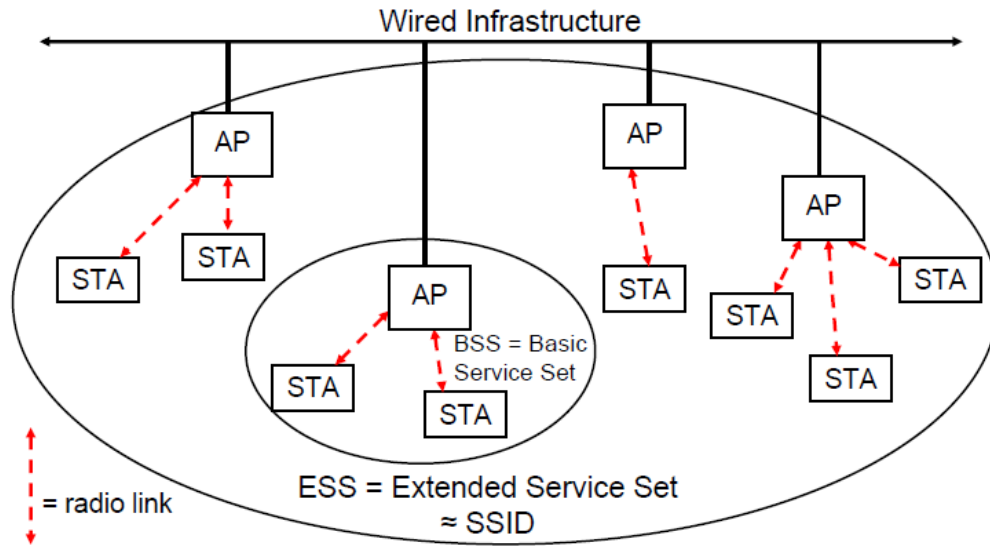
Figure 15.   IEEE 802.11 WLAN structure (From IEEE, 2006)

2.   WiFi Mesh 802.11s

IEEE 802.11s started as a Study Group of IEEE 802.11 in September 2003. It became a Task Group in July 2004. A call for proposals was issued in May 2005, which resulted in the submission of 15 proposals for a vote in July 2005. After a series of eliminations and mergers, the proposals dwindled to two (the "SEE-Mesh" and "Wi-Mesh" proposals), which became a joint proposal in January 2006. This merged proposal was accepted as draft D0.01 after a unanimous confirmation vote in March 2006.

The draft evolved as an informal comment resolution until it was submitted for a Letter Ballot in November 2006 as Draft D1.00. Draft D2.00 was submitted in March 2008, but failed with only 61% approval. A year was spent clarifying and pruning it until Draft D3.00 was created and reached WG approval at 79% in March 2009.

The WiFi Mesh 802.11s structure is described in Figure 16. Here, the BSS are interconnected wirelessly through a Wireless Distribution System (WDS) and also enable a new type of BSS, the so-called Mesh Basis Service Set (MBSS).

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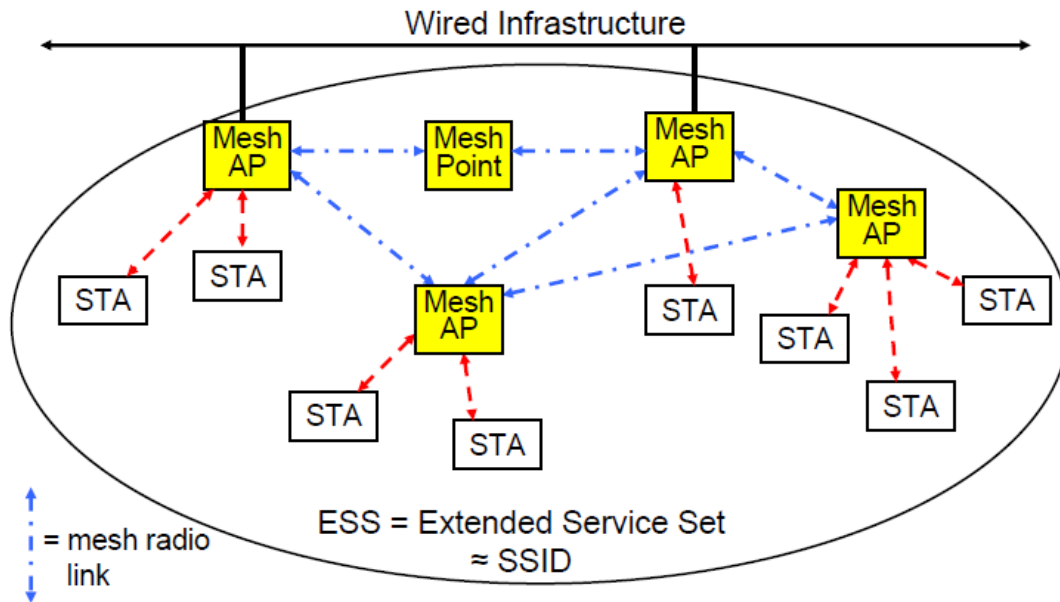
Figure 16.   IEEE 802.11s structure (From IEEE, 2006)

The scope of the 802.11s standard is to integrate WLAN Mesh Networking (WMN) services and protocols at the MAC layer. The main goals of this standard are (Conner, Kruys, Kim, & Zuniga, 2006):

- Create a WDS with automatic topology learning and wireless path configuration

- Establish small/medium mesh networks (~32 forwarding nodes) or larger

- Set up dynamic, radio-aware path selection in the mesh, enabling data delivery on single-hop and multi-hop paths (unicast and broadcast/multicast)

- Become extensible to allow support for diverse applications and future innovations

- Use 802.11i security, or an extension thereof

- Compatibility with higher layer protocols

Since the current standard explicitly states that it does not define the procedures necessary for Wireless Distribution System implementation, many 802.11 multi-hop

implementations do not interoperate (Hiertz et al., 2010). This is the case for HFN center equipment, Rajant Breadcrumb®, and Persistence Systems WaveRelay® IEEE 802.11s solutions.

3.   Rajant Breadcrumb® WiFi Mesh Solution

The Hastily Formed Network (HFN) center provides the Rajant wireless mesh networking equipment from their BreadCrumb® family. The units incorporated into the HFN include a fixed system called the BreadCrumb® LX3, a man-portable unit called the BreadCrumb® ME3, and a smaller portable 2.4GHz BreadCrumb® JR. The Rajant BreadCrumb® LX3 is a rugged, multi-radio, wireless transceiver that forms a mesh network (using the InstaMesh® proprietary protocol) when used in conjunction with other BreadCrumb® devices. This portable, wireless, mesh-network node contains three radios and supports open-standard IEEE 802.11a/b/g protocols to enable data, voice, and video applications. The available radio configurations are: 2.4 GHz/5 GHz/900 MHz, 2.4 GHz/2.4 GHz/900 MHz, and 2.4 GHz/2.4 GHz/5 GHz. This full-featured device can operate in extreme conditions and has several mounting options. One advantage of this system is that it requires little operator intervention and the network is self-forming as LX3 units are added to the network (utilizing their proprietary InstaMesh® protocol) so the network quickly adapts to moving network elements, as illustrated in Figure 17.
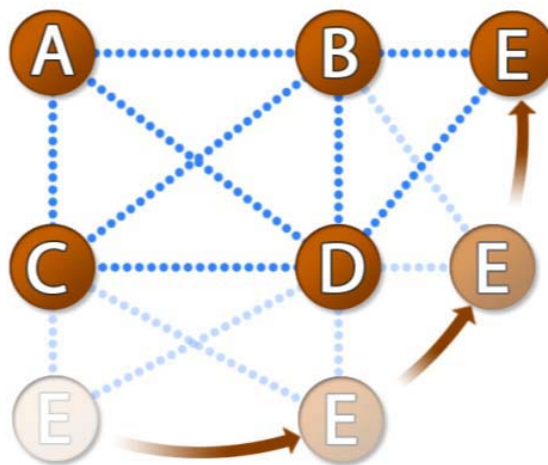
Figure 17.   Rajant Mesh BreadCrumb® (From Rajant, 2011)

The second Rajant BreadCrumb® included in the HFN, the ME3, allows the network to be extended using a man-portable, battery-powered radio with two radios at 2.4 GHz or 900 MHz. The third Rajant BreadCrumb is the portable JR with one radio at 2.4 GHz. Both devices are IEEE 802.11b/g compatible.

Figure 18.   Rajant BreadCrumb® LX3, ME3 and JR (From Rajant, 2011).

Model #	Wireless	Power	Physical
JR	Radio: IEEE 802.11b/g, 2.4 GHz Frequency: 2.402–2.472 GHz Max transmit Power: 25 dBm ± 1 dB	Input V: 10.5–25 VDC Power: 3 W @ 24 VDC	Size: 186 mm x 38 mm x 35 mm Weight: 297g
ME3	Radio: IEEE 802.11b/g, 2.4 GHz or 900 MHz Frequency: 2.402–2.472 GHz or 902–928 MHz Max transmit Power: 2.4 GHz : 28 dBm ± 1 dB	Input V: 6–16 VDC Power: 8 W @ 12 VDC (Not charging) 17 W @ 12 VDC (charging)	Size: 176 mm x 95 mm x 48 mm Weight: 1020 g
LX4	Radio: Frequency: 2.402–2.472 GHz 5.735–5.835 GHz Max transmit Power: 28 dBm ± 1 dB, 28 dBm ± 1.5 dB	Input V: 24 — 48 VDC Power: 23 W @ 24 V (peak)	Size: 195 mm x 187 mm x 61 mm Weight: 2000 g ± 150 g

Table 3.   BreadCrumb® Basic Characteristics (From Rajant, 2011)

All management of the BreadCrumb® system is accomplished using the company's BC|Commander® management tool (Figure 19). This illustrates the view of the health and configuration of the network, as well as the relationships between nodes.

Figure 19.   BC|Commander® Software (From Rajant, 2011)

The following capabilities are offered by the software (Rajant, 2011):

- Topology maps showing BreadCrumb® and client device connections and parameters.

- BreadCrumb®/client device channel, frequency, MAC address, IP address, nickname assignment, signal, and noise levels and time-since-last-update.

- Channel and link speed of connections.

- Manual radio, SSID, DHCP, gateway and port forwarding, access control, security, and encryption settings.

The combination of hardware and software provided by Rajant, with its ease of operation and intuitive software, makes the BreadCrumb® Wi-Fi mesh networking solution a good choice for the HFN.

4.   Wave Relay Solution

The other WiFi Mesh related equipment provided by the HFN center is the Persistent Systems Wave Relay™ solution. This is an advanced Mobile Ad Hoc Networking (MANET) solution that goes beyond the standard "self-forming" and "self-healing" mesh network. Instead, Wave Relay™ quickly and continuously adapts to fluctuations in terrain and other difficult environmental conditions to maximize

connectivity and communication performance. The Wave Relay™ proprietary routing algorithm allows users to incorporate vast numbers of meshed devices into the network in which the devices themselves form the communication infrastructure (Persistent-Systems, 2011).

Persistent Systems describes MANET as a collection of mobile devices (often referred to as "nodes") that form a self-configuring network. The devices communicate wirelessly by relaying data across the network through a sequence of transmissions. In a true MANET, such as Wave Relay, every node can communicate with every other node enabling true peer-to-peer connectivity. This is in marked contrast to the far more common mesh network design, in which a series of stationary access points connect end users only to the Internet (Persistent-Systems, 2011). The Wave Relay MANET is designed to maintain both peer-to-peer routes and connectivity to an Internet gateway while under mobility. The system detects changes in connectivity and, using a revolutionary routing protocol, elegantly adjusts the pathways in order to maintain the most efficient route between them (Persistent-Systems, Persistent Systems Technology-Mobile Ad Hoc Networking, 2011).

Persistent Systems details the main differences between WiFi Mesh and MANET in Table 4:

Features	Mobile Ad hoc Network	Mesh Network
Any-to-Any Routing	YES	NO
Routing to Gateway/Internet	YES	YES
Mobile Routers	YES	NO
Users included in routing	YES	NO
Fault Tolerant Architecture	YES	NO
Military capable	YES	NO
Public Safety capable	YES	NO
Designed for Industrial Apps	YES	NO

Table 4.   MANET vs. Mesh Networking (From Persistent Systems, 2011)

Though a mesh network and a MANET may appear similar at first, a closer look reveals significant differences in their capabilities (Persistent-Systems, Persistent Systems Technology- Mobile Ad Hoc Networking, 2011).

Problems with Traditional Mesh	Wave Relay Solution
Client computers use consumer-grade 802.11 radios that do not operate dependably over long distances or through obstructions.	Meshed radios bring the AP straight to your computer. Data is routed efficiently through other meshed CPEs in the area.
Weak signals between end-users and APs located outside homes and offices results in lower bandwidth. (Usually 1Mbps shared among all area users.)	Meshed end users share a huge 54 Mbps of bandwidth.
Single-radio mesh networks must forward data through the mesh on the same radio they use for client connectivity.	Data is forwarded through the mesh by peer-to- peer routing. Quad Radio Architecture incorporates four meshed radios operating on different channels.

Table 5.   Traditional Mesh problems and MANET solutions (From Persistent Systems, 2011)

In the broad Wave Relay family of products, the QUAD Radio Router is the one that is most employed. It offers deployment flexibility, robust fault tolerance, and scalability for large MANET systems, all in a compact and rugged package. It contains up to four separate wireless radios, all of which participate in the routing. The Quad Radio Router includes five 10/100 Mbps Ethernet ports that are IP67 rated and designed for outdoor use. An integrated NATO Audio 6-pin U-283/U connector enables standard push-to-talk headsets and speaker boxes to be connected to the system. Two RS-232 serial ports are available that enable serial-over-Ethernet connectivity. It can be vehicle mounted for mobile deployments, mast mounted to cover large geographic areas, and/or paired with a Tracking Antenna System Kit to provide long-range air-to-ground connectivity.

Figure 20.   Quad Radio Router (From Persistent Systems, 2011)

In its standard configuration, the Quad Radio Router contains four embedded radio modules that operate in the 2.3–2.5 GHz and 5 GHz frequency bands, but the routers can be configured differently to support other bands. By utilizing multiple radios on different channels, bandwidth is preserved across multiple hops. The Wave Relay™ Quad Radio Router is capable of forwarding up to 27 Mbps of TCP throughput across multiple wireless hops. It has five (5) Ethernet ports designed for outdoor use. One port (Ethernet 1) accepts injected Power-over-Ethernet (PoE), and all ports are able to connect to external devices in the mesh. Operating at Layer 2, Wave Relay™ seamlessly bridges any device that runs over Ethernet. The Quad Radio Router has an integrated GPS receiver that allows direct integration with the Wave Relay™ Network Visualization System (based on Google Earth), providing real-time network visualization and tracking. In addition, security and encryption has been tested by independent test labs—as well as by NIST—and has been validated to meet the FIPS 140–2 Level 2 specification (Persistent-Systems, Quad Radio Router, 2011).

Among the system features, two were particulary useful during the experiments. One is the Google Earth Network Visualization System that provides real-time GPS tracking of each node, and of link performance, using color-coded lines. Figure 21 shows the Google Earth web page with the Wave Relay^{TM} information attached.
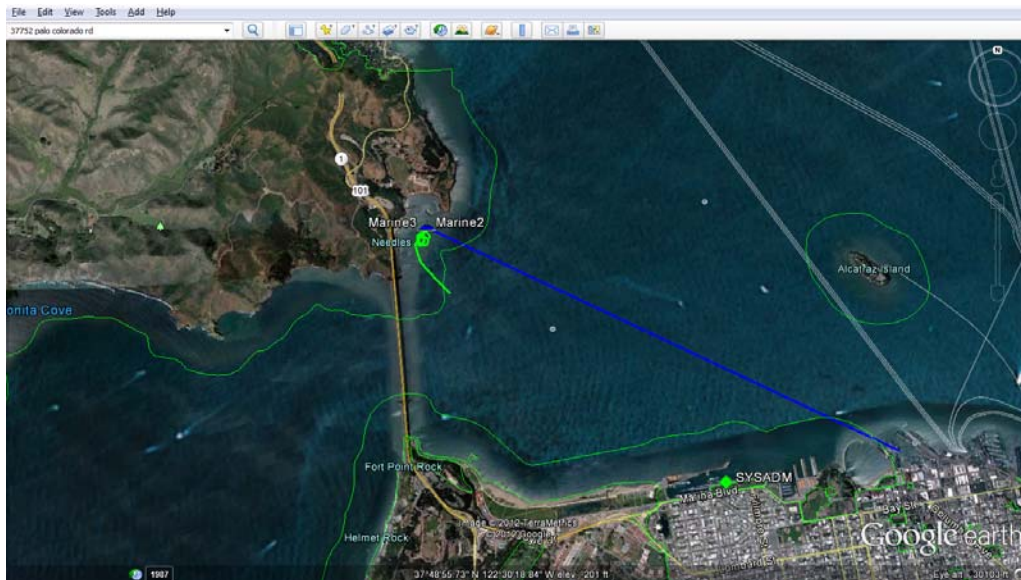
Figure 21.   Google Earth Network Visualization with Wave Relay solution

The other notable feature is the real-time Signal-To-Noise Ratio (SNR) information tool that the GUI provides. This information is important when users are setting up the system in a fixed configuration and also when a node, moving far away from other nodes, tries to reconnect to the network. Figure 22 shows some real case SNR information provided by the Wave Relay GUI.
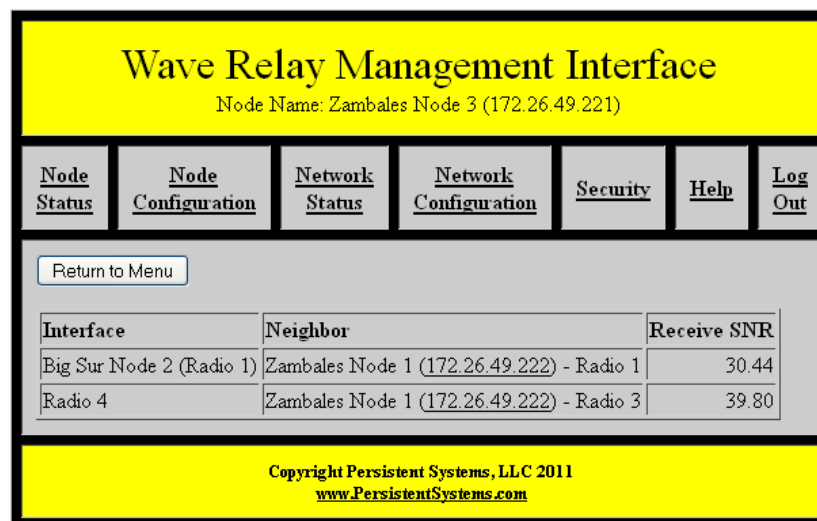
Figure 22.   Wave Relay^{TM} GUI with SNR information

5. Antennas

Besides the 5 GHZ antennas described earlier, the Comet SF245-R 2.4 GHz antenna—a mono-band, omni-directional, 7.4 dBi gain, and fiberglass antenna—was employed during the exercises and demonstrations.
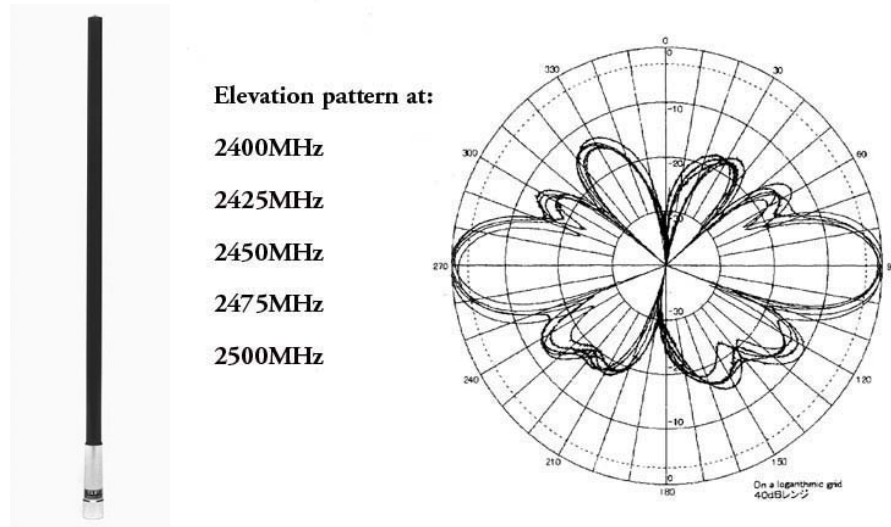
Figure 23.   COMET SF245R Antenna and elevation pattern (From Microcom Technologies, 2005)

C.   SATELLITE DATA SYSTEMS

1.   Broadband Global Access Network (BGAN)

The HFN center uses a Broadband Global Access Network (BGAN) as the primary initial backhaul method to connect with the Internet or backbone. The BGAN is a global Satellite Internet Network with telephony using portable terminals. The terminals are normally used to connect a laptop computer to broadband Internet in remote locations although—as long as line-of-sight to the satellite exists—the terminal can be used anywhere. The value of the BGAN terminals is that, unlike other satellite Internet services which require bulky and heavy satellite dishes to connect, a BGAN terminal is about the size of a laptop and can be easily carried. The network is provided by InmarSat and uses a network of three geostationary satellites called I-4 to provide global coverage except for the poles. The actual coverage of BGAN service is depicted in Figure 24.
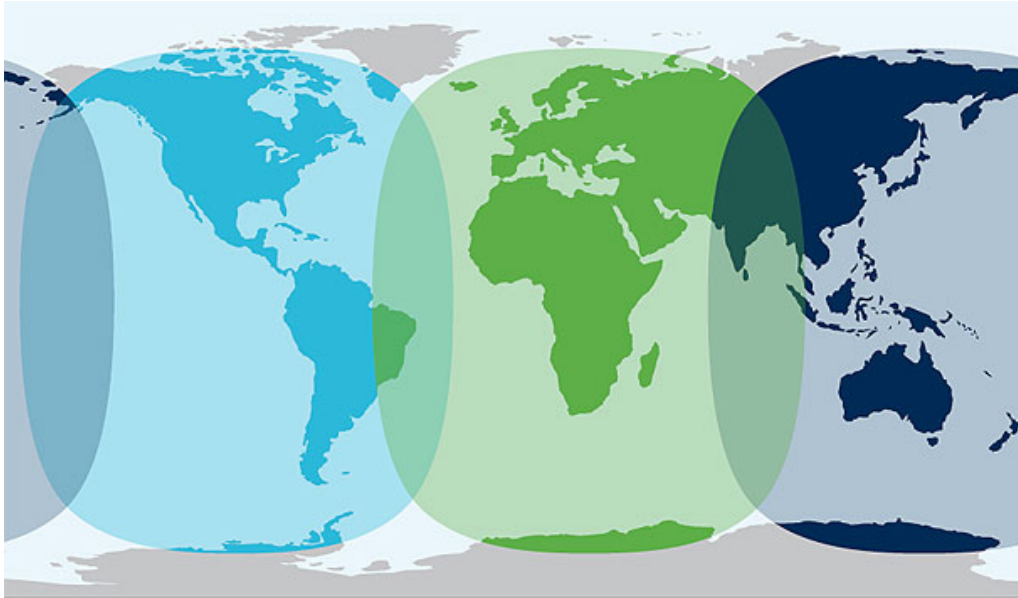
Figure 24.   BGAN global coverage (From InmarSat, 2012)

BGAN terminals can be classified as Land Portable (class 1 or class 2), Military (land portable or vehicular), and Vehicular. Land Portable class 2 equipment supports 32, 64, 128, 176, or 256 kbps. Land Portable class 1 equipment supports the same data rates and BGAN X-Stream™ (492 Mbps symmetrical up-down data stream). Even though it provides near global coverage, InmarSat only supports vehicular 256kbps streaming at elevations above 45 degrees. Below this elevation, the 128 kbps streaming connection is recommended.

2.   InmarSat BGAN HUGHES 9201 and 9202 Terminals

The HFN center has two Hughes Network Systems LLC terminals: the Hughes 9201 BGAN and the Hughes 9202 BGAN. Both are lightweight Land Portable terminals that are rechargeable-battery operated with built-in WiFi, ISDN, POTS, fax, and Ethernet capability. They are water and dust IP-55 compliant. The main differences are that the 9201 is a class 1 (up to 492 Kbps X-Stream^{TM} capability) and the 9202 is a class 2 (up to 256 Kbps), and they have different GUIs to program and configure.

Figure 25.   Hughes 9202 and 9201 BGAN terminals (From Hughes, 2010)

3.   InmarSat BGAN HUGHES 9450 On-the-Move

The Hughes 9450 BGAN terminal is a vehicular, highly compact, and high-performance system that supports up to 128 symmetrical streaming IP connections. The 9450 terminal is composed of four core component parts: the transceiver or Indoor Unit (IDU), the antenna or Outdoor Unit (ODU), the power connector/cable, and an 8-meter RF cable. The IDU has multiple interfaces: four PoE/Ethernet (RJ-45), one ISDN, two POTS (RJ-11) and WiFi IEEE 802.11b.

Figure 26.   Hughes 9450 IDU and ODU units (From Hughes, 2010)

4. InmarSat BGAN Thrane & Thrane Explorer 700

The last BGAN terminal employed in the experiments is the Thane & Thrane Explorer 700. This is a Class 1 (supports InmarSat's BGAN X-Stream, on-demand streaming service at +384 kbps) and Land-Portable type terminal. The terminal is designed as two separate units so the antenna can be placed outside while an operator works indoors. Given its broad bandwidth, it supports multiple users sharing a single unit, enabling an instant broadband LAN. It has two Ethernet ports, Bluetooth, two ISDN ports, and WiFi interfaces, and it can operate with internal rechargeable batteries or an external multi-voltage power supply.

Figure 27.   BGAN Thrane and Thrane Explorer 700 (From Thrane & Thrane, 2011)

D. CELLULAR DATA SYSTEM

1. Cellular System Overview

Mobile telephone service originated in the late 1940s, but the early system was never widely used because of its limited frequency-spectrum allocation and the high cost of the required equipment. Semiconductor advances, frequency spectrum reallocation, and ingenious system designs were able to bring the cost under control by the late 1980s (Beasley & Miller, 2008). Cellular mobile radio service is commonly referred to as mobile telephone service, what is true in the first generation of cellular systems. In 1971,

AT&T proposed an analog cellular phone system called AMPS (Advance Mobile Phone Service), what is now considered the first generation of cellular systems. It operates in the 800 to 900 MHz band range, with Frequency Division Multiple Access (FDMA), frequency modulation, and 30 KHz channels. In 1991, a digital technology called Time Division Multiple Access (TDMA) was introduced in the market by AT&T, and at almost the same time Western European countries introduced the digital Global System for Mobile Communications (GSM). In 1995, the U.S. company Qualcomm introduced Code Division Multiple access (CDMA) to compete with GSM. Considered the second generation of cellular systems, they introduced text messaging and data transmission. The 3G (or third generation) wireless system was developed to provide broadband network services with expected data rates exceeding 2 Mbps. The standard defining 3G is called International Mobile Communications, or ITM-2000, and it introduced Wideband Code Division Multiple Access (W-CDMA). In the interim there were additional technology upgrades. Most wireless providers offered 2.5G and 2.75G, called GPRS (Global Packet Radio Service), and EDGE (Enhanced Data-rates for Global Evolution) with data rated between 2G and 3G (144 to 244 Kbps) (Beasley & Miller, 2008).

The successor of 3G is ultra-broadband Internet access, called 4G, and it was defined in 2008 by the International Telecommunication Union-Radio (ITU-R) and the International Mobile Telecommunication Advance (ITM-A). There are 2 standards under development and use: the Mobile WiMAX and the Long Term Evolution (LTE), which provide peak data rates up to 100 Mbps. The huge difference between this latest generation and earlier ones is that 4G does not support traditional, circuit-switched telephony service. Instead, it supports Internet-protocol (IP) based communication, such as IP telephony. 4G also adapted OFDMA as an access method, as described previously in this chapter.

2.   Lockheed Martin MONAX System

MONAX (Mobile Network Access) from the Lockheed Martin Corporation is fundamentally a deployable, secure, highly proprietary improved 3G private network to leverage smart phone applications and capability, developed both by the organization that

uses MONAX and by outside entities. The present version of MONAX uses a technology called Time Division-Code Division Multiple Access (TD-CDMA), which is a channel access method that uses a spread spectrum across multiple time slots. It has been shown that a mixture of TDMA and CDMA provides better quality of service for multimedia communications in terms of data throughput and voice/video quality. 4G LTE technology is in Lockheed Martin's roadmap for future versions of MONAX. The system operates in 700 MHz—a frequency band that has been reserved for the foreseeable future in the U.S. for first responders—but this could change according to customers requirements.

MONAX systems have two main components: MONAX Base Stations and MONAX Lynxs. MONAX base stations have either one or three sectors, with each sector supporting 250 simultaneous users. Range and throughput is a function of multiple factors. The whole base station is contained in a transit case plus its cables, antennas, and mast, so it can be easily transported and deployed. The MONAX Lynxs are slim, lightweight 'hot spots' that use the secure, encrypted, TD-CDMA 700 MHz channel to connect to the base station and an IEEE 802.11b WiFi access point (AP) to integrate smart phones and any WiFi-capable devices. The system is completed with a software application and different alternative power sources.

Figure 28.   MONAX Base Station and MONAX Lynx (From Lockheed Martin, 2012)

Figure 29 shows the MONAX architecture with its main components.

Figure 29.   MONAX Architecture (From Lockheed Martin, 2012)

With this architecture, the secure broadband network system connects off-the-shelf smart phones to a cellular base station infrastructure, enabling users to securely send and receive data-rich information to its users. A secure RF Link protects communications through strong, exportable encryption, enabling the transfer of pertinent and sensitive information. MONAX can connect hundreds of users to a single base station.

E.   RESEARCH DESIGN

1.   Background

The demonstration experiments are designed to illustrate how specific issues, approaches, and/or federations of systems can provide a utility for a targeted group (Alberts & Hayes, 2009). In this thesis, we use field demonstration/experimentation that was performed in several locations: Big Sur, California; Kaneohe Bay, Hawaii; Subic Bay, Philippines; and Salinas, California. Even though each field experimentation had its

specific purpose, all of them were developed with the generic purpose of demonstrating

how the COTS technology could increase the capacity of the HFN to respond better to HA/DR operations.

The experiments were framed by the HFN concept:

The ability to form multi-organizational networks rapidly is crucial to humanitarian aid, disaster relief, and large urgent projects. Designing and implementing the network's conversation space is the central challenge. (Denning, 2006).

The actual environment of each experiment—where uncertainty about requirements, resources, and terrain conditions was the norm—was duplicated in our HA/DR efforts.

### 2.	System Architecture

The HFN center works with other organizations to develop an information system that communicates all relevant information to the Emergency Operation Center (EOC). The EOC also uses this HFN to coordinate disaster relief efforts. Even though there is no rigid architecture that can match all HA/DR missions, a basic schema is depicted in Figure 30:
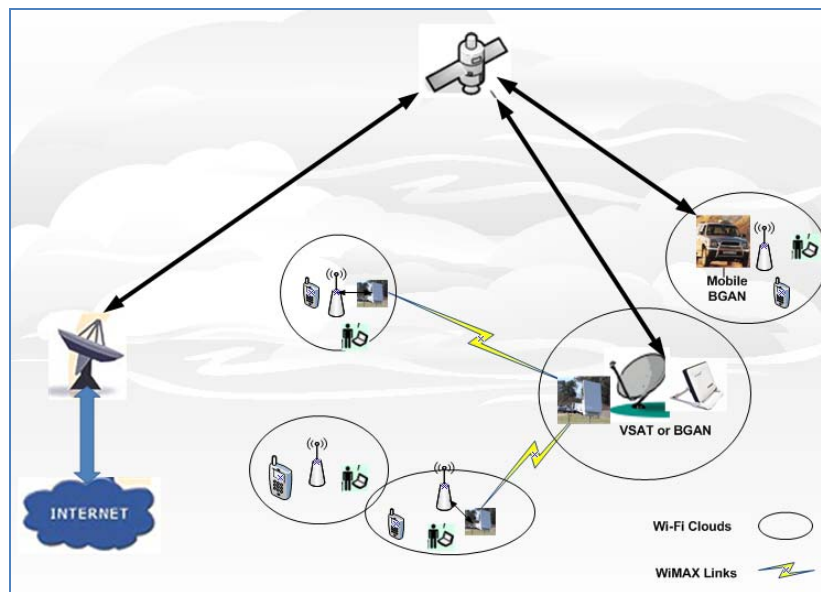
Figure 30.	Basic HFN architecture

3. Experiment Matrix and Design.

Several experiments were developed which provided HFN center members the opportunity to both test the components individually and also to integrate those components into the designed system. Table 6 lists the experiments and their dates.

Date	Location	Description
4/3–4/5/2012	Big Sur, Ca	IPC3 field demonstration
2/20–2/24/2012	Kaneohe Bay, Hi	Double Jeopardy Exercises
4/16–4/25/2012	Subic Bay, Philippines	BALIKATAN 12 exercises
5/24/2012	Salinas, Ca	Wave Relay Field Test

Table 6.   Experiment Matrix

The HFN concept is a continuously evolving idea and, as such, the design of the experiments was driven by the requirements of the sponsors. From them, this thesis analyzes the following issues:

- Coverage area of different WiFi solutions

- Range of WiMAX links

- Throughput of BGAN satellite links

IV.   EXPERIMENTS AND EXERCISES

A.   EXPERIMENT ONE: BIG SUR IPC3 EXERCISE

1.   General Description

The first experiment took place from 3–5 April, 2012. The NPS Independently Powered Command/Control/Communication Program (IPC3) and the Hastily Formed Networks center (HFN) conducted a field exercise, demonstration, and conducted various experiments for the Monterey County Consortium in a humanitarian assistance/disaster relief (HA/DR) scenario of a fire conflagration event in and around Big Sur, California. The team consisted of NPS faculty and students, regional early responders from several jurisdictions, California National Guard, Coast Guard representatives, InmarSat representatives, AvWatch (manned aircraft contractor), as well as members of the California Homeland Security Consortium (CHSC). The regional agencies that participated included NPS, CAL FIRE, SALINAS FIRE DEPT, MONTEREY COUNTY OFFICE OF EMERGENCY SERVICES, CALIFORNIA STATE PARKS, MONTEREY AIRPORT DISTRICT, and CAL EMA/SACRAMENTO. The NPS participants were:

- Brian Steckler, Albert Barreto: NPS IPC3 faculty research leads.

- Christian Gutierrez, Mark Simmons, Eid Al Khatani, Mahmut Firuz Dumlupinar, Stanley Wong, John Sims, Khaled Ferchichi, Marvin Peredo, Marcelo Perfetti: NPS students.

- Jim Zhou: Information Technology and Communication Services (ITACS) staff member.

- David Huey: Information Science researcher.

- Chris Clausen: Remote Sensing researcher.

The IPC3 team deployed VSAT and BGAN for satellite reach-back to the Internet Protocol (IP) backbone at both pre-designated and "on the fly" locations, as directed by the County early responders, in a scenario that was as realistic as possible. The primary goal of the event was to establish voice, video, and data communications in an austere

environment where normal the information-communication technology (ICT) infrastructure is degraded and/or denied. This was an HA/DR scenario where there was no cellular service, no surviving copper/fiber data networks, and no push-to-talk radio infrastructure (or at least not enough to cover all affected areas). An IP backbone with a meshed Wi-Fi infrastructure and some links via WiMAX—all enabled with Internet access by the VSAT and BGAN terminals (with an extension of the Wi-Fi mesh via fixed wing manned aircraft)—was the method we used to mitigate the unavailability of a normal ICT infrastructure. A secondary goal of the event was to provide training as appropriate for NPS students, the California Homeland Security Consortium, and other Monterey County Early Responders.

The three following designated locations in the Big Sur, California area were tied together wirelessly:

- An Emergency Command Post at the U.S. Navy (NPS) facility/land at the Point Sur lighthouse complex. This location had been deemed suitable for a mobile NOC and was equipped with a shelter and supplies.

- An Incident Command Post with a few tents, one Monterey County mobile command center, and one California National Guard mobile command center at Andrew Molera State Park (AMSP).

- An Incident Command Post along the Old Coast Highway.

The AMSP site also served as the end-of-day, overnight camping site for the evenings of April 3 and 4. The main force wanted to add to the realism of a major disaster by staying on site with the gear. Also, many did not want to waste time tearing the camp down and moving from the area each day, using up valuable and scarce daylight hours, since the event was only three days long.

The scenario was a major fire event that reached the woods above the area from east of Pt Sur down south to the east of Big Sur proper. The County Emergency Manager declared the area a disaster and implemented the mutual aid agreement. NPS was called to assist, via proper channels and within guidelines of the National Response Framework, using IPC3-provided technology suits of ICT gear. NPS personnel were embedded with

Monterey County early responders as appropriate. Scenario inject details were being provided in a separate document via e-mail.
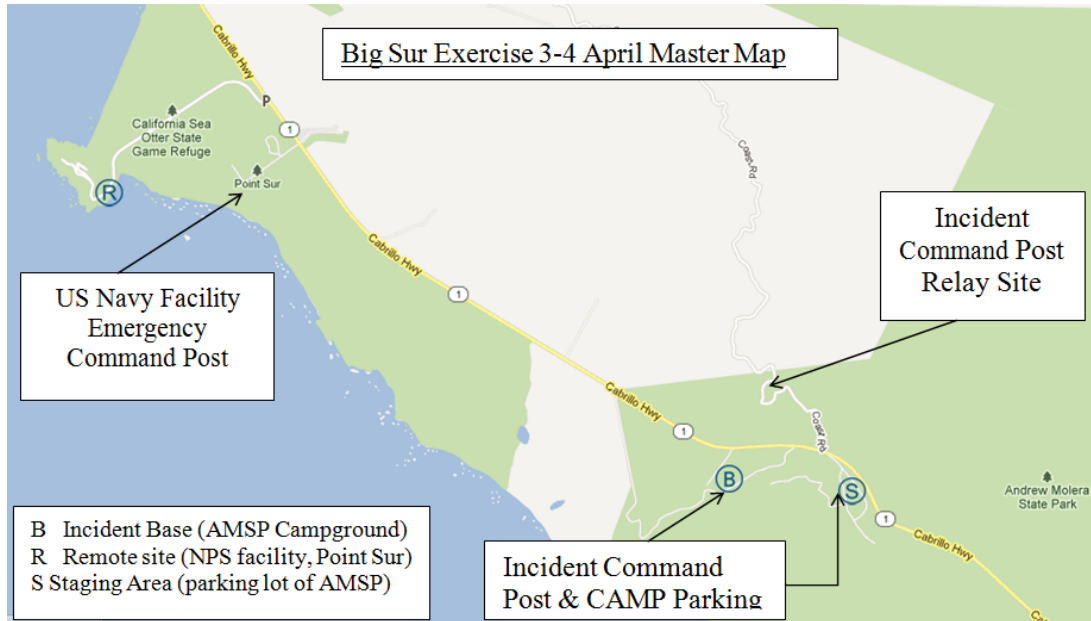
Figure 31.   Big Sur Exercise – Master Map

This exercise was characterized by its large number of participants and the relative ease of access and transport of gear to the area. More than eleven different organizations participated in the exercise, collaborating and inter-exchanging experiences and results. This was a realistic scenario of an HA/DR effort where many qualified technicians with sophisticated equipment assisted and collaborated in the relief of an emergency situation. This environment required leadership and strong coordination from the organizing institution, a need that was delivered successfully. The expertise of each organization increased the performance of the whole system, given the dialogue and collaborative atmosphere. In addition, given the proximity of the area with NPS and transportation companies, most participant organizations arrived with big, heavy, and non-fly-away equipment that provided redundant and high-capacity resources to the experiment. For example, the NPS HFN center transport required equipment in Nemesis (Communication Center in a Motor-Home) and in a large flatbed truck; InmarSat shipped a small auto-deployable VSAT terminal by UPS; and the California National Guard

drove down to Big Sur with one mobile communication center with two 1.2-meter VSAT antennas and one command operation center.

Figure 32.   AMSP Campground

During the exercise, an unforeseen situation was added to the planned injects, a real-world problem introduced by the California State Park: three hikers of different ages were lost in different areas of the State Park. Immediately, the exercise was reconfigured to support those rescue activities. Maps, cartography, data, radio and telephony communications were established to support the real-world operation. Fortunately, at the end of April 4th, two of the three hikers were rescued by State Park rangers. The third hiker, lost in another part of the Monterey County regional forests was still missing at the end of the exercise and subsequently died.

2.   Experiment Results.

There were thirteen different planned injects for this exercise, plus a real-world case inject. In terms of the focus of this thesis, only BGAN, WiMAX, and Mesh Wi-Fi performances were analyzed.

a.   BGAN

During the exercise, satellite systems were used as the primary backhaul method to connect with the Internet service Provider (ISP) or backbone, as the HFN concept implies. Originally, the InmarSat BGAN systems were the ones being used at AMSP, but the California National Guard provided two 1.2-meter Very Small Aperture

Terminals (VSATs) with 2 Mbps of bandwidth, and InmarSat also provided one 0.9 meter VSAT with 1.5 Mbps, both operating in Ku band. This equipment does not operate with internal batteries, so Honda gas generators were used to provide energy at the AMSP site all day long. Complementary solar panels, a hydrogen fuel cell, and a wind turbine with battery packs were installed in the area, but they could not provide enough energy for the whole system and were only used for the EOC in a Box.

Figure 33.   California National Guard and InmarSat VSATs

The BGANs (Hughes 9201 and 9202) were assigned to the Navy Facility in Point Sur and to the Old Coast Road Incident Command Post (ICP). They played an important role as back-up systems, while the WiMAX and WiFi Mesh were being installed. They provided Internet access at 200 Kbps down-link and 90 Kbps up-link that allowed users to run VoIP and chat applications during the exercise (Skype application). Their main advantages were the speed of setup, the built-in battery system that provided service without external power for at least four hours, and the built-in WiFi access point for Internet access.

The Hughes 9450 On-The-Move BGAN was mounted in an SUV and played an outstanding role during the whole exercise, providing Internet connectivity from the time vehicles departed from NPS until they came back three days later. Its performance was slightly lower than the Hughes 9201 and 9202 when moving, but equal

when stationary. As with the other BGANs, it was mostly used to run a Skype application for chat. One specific inject was prepared to test the capability of providing live video feeds of the fire area and maintaining voice communication at the same time, but the file transfer capability was not measured specifically.

b. WiMAX

The NPS HFN team prepared four pairs of Redline WiMAX in bridge mode: two with one-foot-square directional antennas and two with two-foot-square directional antennas. The radios were configured and labeled in the HFN lab before the exercise to avoid confusion in the field, and were supposed to be installed in bike-tripods. The first day of the exercise, the team attempted to link the three sites with WiMAX links without using a repeater. The first link was easily achieved as expected because of the short distance and the direct line of sight (LOS). However, data-transfer measurement and signal, noise and distortion ratio (SINARD) levels varied continuously from high to low values.

After consulting experienced technicians, we found that the wind and bad radio installation were the cause of this problem. First, even though there was a clear LOS between the two points, students tended to install the antennas as high as possible, making the winds oscillate the antenna more. This problem was fixed by putting both antennas as low as possible, thus lowering the oscillation. At this point, the link became more stable; however, in order to make it even better a student replaced the tripod with fence poles that were very firm. Once the radios were on the poles, the link showed minimum change in performance at high data rates (40 Mbps). Second, we were using very big antennas (twice as much area as the 1 foot by 1 foot panels) that presented a high wind-load coefficient. This issue generated new ideas among NPS students about how to improve WiMAX equipment installation in a HFN environment. In future exercises, different antennas with small wind loads will be tested to evaluate possible solutions.

Figure 34.   Different WiMAX installation at Old Coast Road

The second link was between the Old Coast Road and the Navy Facility at Point Sur.
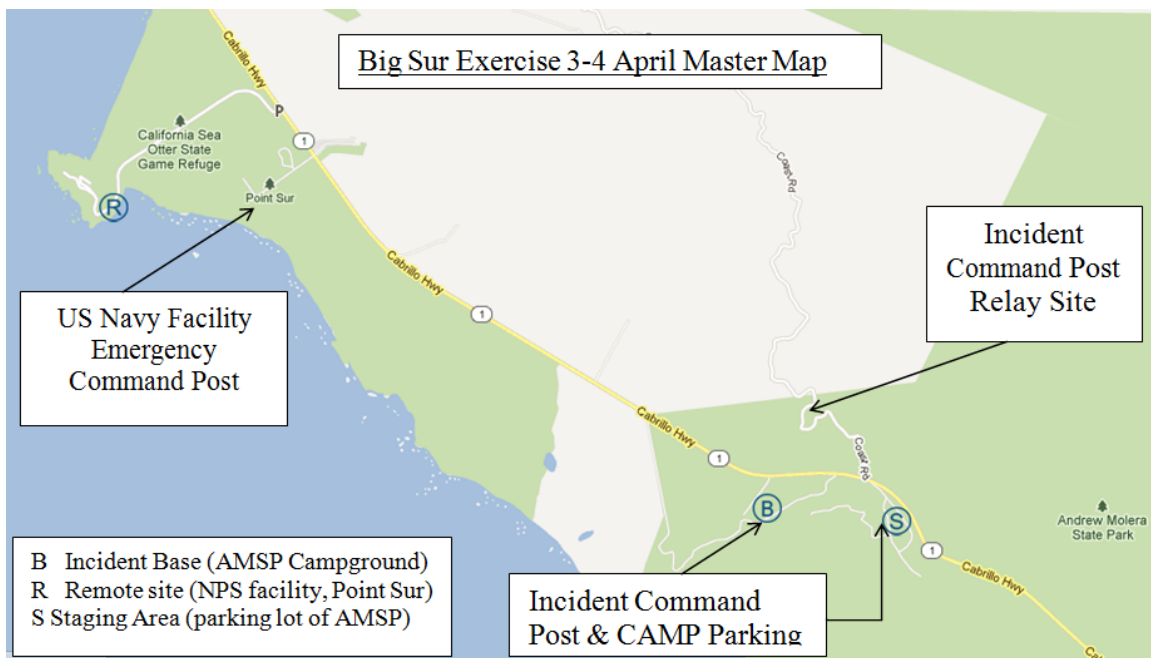
Figure 35.   Big Sur Exercise Master Map

This was a difficult link according to previous analysis because of a single large obstruction in the terrain profile. This was a 2.2-mile NLOS link. The Navy Facility is near sea level (38 feet) and there is a huge forest in the transmission path. In spite of several attempts, the link could not be achieved. The Red Line built-in spectrum analyzer showed no signal level, and the direct link between both sites was aborted. Figure 36 shows the link terrain profile for this unsuccessful link.
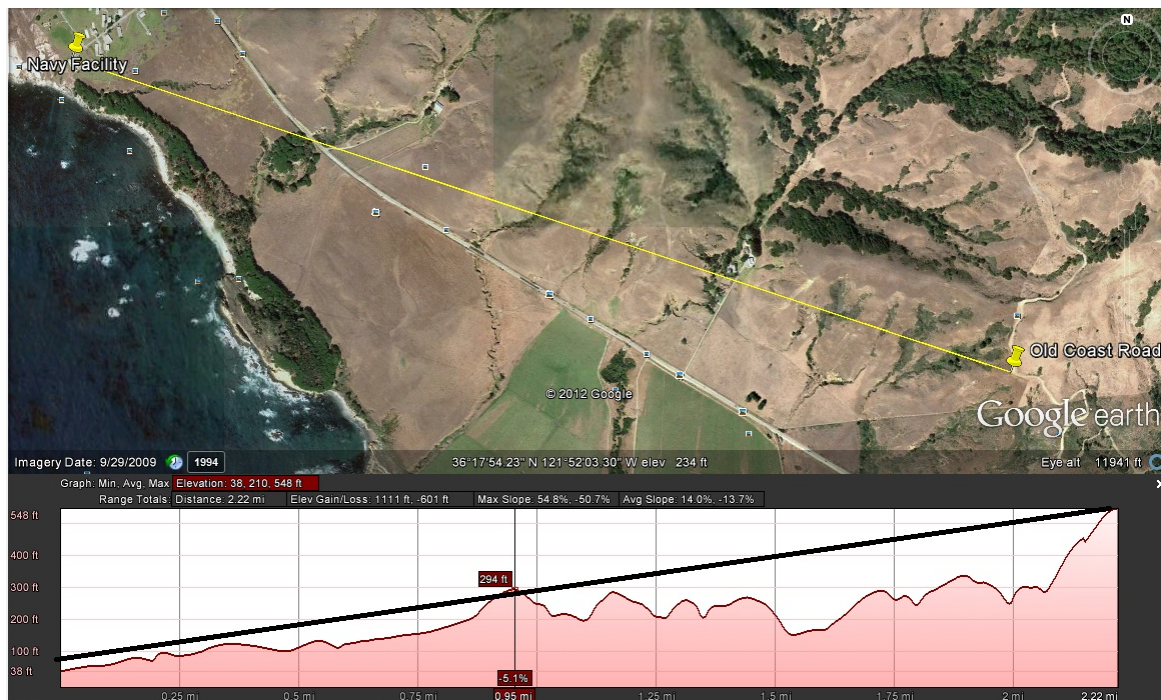
Figure 36.   Google Earth link terrain profile between Navy Facility and Old Coast Road

For the second day of the exercise, the NPS HFN team prepared a different solution for this link. At this point it should be mentioned that there were additional limitations to the generation of better solutions. The work area was limited to AMSP, the Navy Facility, and Highway 1. Other private surrounding areas and the Point Sur Lighthouse area were banned from being used. The solution involved the installation of two more bridges along the highway, thus avoiding the elevation and the forest that blocked the RF signal. The first bridge was completed successfully, but the next task was

suspended due to the lack of time, personnel, additional activities, needing attention, and the success of the WiFi Mesh solution.

Figure 37.   Planned WiMAX links for 2nd day of exercise

At this point, the team discovered that a power source other than the Honda gas generator would be more appropriate for speeding up WiMAX installation in HA/DR situations. Also, the big antennas were found inappropriate for these short links where access to points of installation were so complicated. All in all, the team realized that the Red Line WiMax with big antennas and a gas generator as power supply did not meet the requirements of this scenario. Such antennas are more suitable for long range links with stable structures.

c.   Wi-Fi Mesh

There were three injects in the ICP related to the WiFi Mesh systems. The first involved to the set up of a Wave Relay WiFi Mesh network in the three locations: the AMSP Campground Incident Command Post, the Remote Command Post at the Navy Facility at Point Sur, and the ICP at Old Coast Road. The second was related to aerial video intelligence gathered from the fixed-wing, manned aircraft assigned to the event from AvWatch Inc. (an Airborne Technology Company for homeland security

professionals). The last inject was related to ground video intelligence gathered by one Field Observer team (FOBS) on the ground. These three activities were led by Coast Guard LT Ryan Kowalske (First Coast Guard District Enforcement) and Bob Griffin (AvWatch Inc.).

For the first inject, the WiFi Mesh team started developing the network, installing two Wave Relays at AMSP Campground. One Wave Relay was configured to provide Internet service to the entire network through a Cisco Router that was connected to an InmarSat VSAT terminal. This Cisco Router was already configured to create a Virtual Private Network (VPN) with the Coast Guard Experimentation Network on the East Coast. Therefore, AMSP ICP had voice, data, and video connectivity with Wave Relay Stations located in Boston, New York, and Florida. The second Wave Relay was installed at the center of the AMSP ICP to provide WiFi Internet access to mobile users and to link (with another of the four radios) from AMSP to the Old Coast Road ICP, where the WiMAX repeater was going to be installed. Though the WiMAX link would not be very hard to achieve, this team made it easier. Instead of using a directional antenna that requires more stability and pointing, they used a 60° sector antenna. Though it has less gain (dB), it offered less wind load and was easier to point. At the Old Coast Road ICP, the team applied a similar solution to antennas in order to close the link. They employed a 120° sector antenna, more than was required to get strong SNR and throughput.

Figure 38.   Wave Relay at AMSP and Old Coast Road

In order to link Old Coast Road with the Navy Facility at Point Sur, the WR team installed two repeaters along the road in the same places that WiMAX planned their installations. However, at this point the WR team successfully completed the task (given the flexibility of the Wave Relay technology), and they used omni-directional antennas and small external batteries to power the units. Since each Wave Relay has four radios, only one Wave Relay is necessary to build a repeater and Access Point at every site. One radio was used for the uplink towards AMSP ICP, a second one for the downlink towards the Navy Facility, and a third one provided a WiFi access point to mobile devices. Finally, the last Wave Relay unit was installed at the Navy Facility, providing Internet access to the Remote ICP installed at this location. Ryan Kowalske and his team discovered something amazing at this point: the Wave Relay WiFi Mesh system was able to connect the Navy Facility to the Old Coast Road site (3.5 Km-2.2 miles) directly with omni-directional antennas and NLOS (in the 5.8 GHz band) without an intermediate repeater, but with a low bandwidth. Figure 39, taken from Google Earth and running Wave Relay Visualization, shows the behavior of the WiFi Mesh system.

Figure 39.   Wave Relay network visualization in Google Earth (From Ryan Kowalske, 2012)

The second incident developed for this exercise was related to aerial video intelligence gathering from fixed-wing, manned aircraft assigned to the event from

AvWatch Inc. The manned aircraft are designed to overfly the area under fire and transmit real time information to the ICP located in AMSP. In order to achieve this, the aircraft were equipped with a pan-tilt-zoom, digital camera connected to a Wave Relay radio which transmitted this information to an auto-tracking antenna attached to the Wave Relay Node at AMSP. Unfortunately, the auto-tracking antenna system that should have provided up to a 100-kilometer range with LOS malfunctioned, so an omni-directional antenna was used instead. Despite this problem, the system was able to provide a video stream to the AMSP Incident Command Post up to 10 Km. Figure 40 shows the non-operational, directional antenna, a screen shot of the Google Earth visualization of the entire system, and the video stream received at the command post itself.
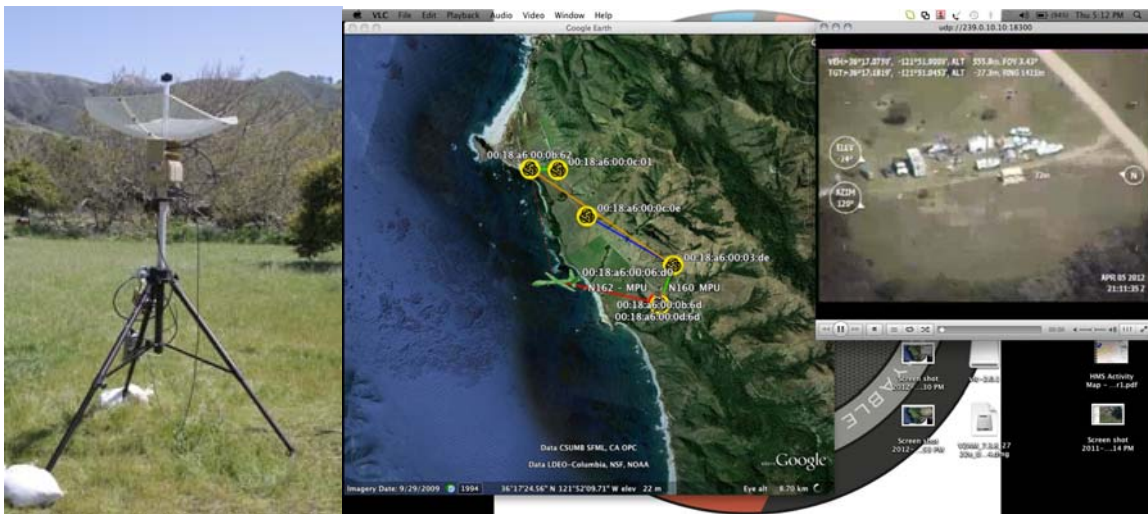
Figure 40.   Wave Relay directional antenna, Google Earth visualization and video stream screen shot (From Ryan Kowalske, 2012)

The last exercise inject for the WiFi Mesh experimentation was ground video intelligence gathering from a FOBS on the ground. With equipment brought and operated by LT Kowalske the team captured video with a wireless web camera installed on a helmet and transmitted real-time video to a Wave Relay, man-portable unit. This video stream was retransmitted to a video stream server located in Boston through the described WiFi Mesh and Internet VPN. At the same time, the FOBS talked to viewers on the other side of the country (the East Coast) via VoIP provided by the Wave Relay, man-portable

unit. The video/voice system worked successfully all around the AMSP ICP until the operator clearly lost LOS to the Wave Relay base station (200 to 300 meters).\

Figure 41.   LT Ryan Kowalske operating real-time video and VoIP Wave Relay system

The WiFi Mesh team met and overcame the exercise injects despite equipment failures (directional antenna) and site access problems (forbidden areas).The Wave Relay WiFi system proved that it can provide long-haul links and wide, local-area coverage with short set up times. Google Earth visualization was a helpful tool in administrating the network and maintaining command and control of all assets during the emergency. Google Earth Visualization also requires technical expertise and previous configuration to leverage all of its capabilities.

B.   EXPERIMENT TWO, DOUBLE JEOPARDY, KAENOHE BAY, HI

1.   General Description

The second experiment took place in Kaenohe Bay (Hawaii) from 20–25 March, 2012. The Marine Corps Forces Pacific (MARFORPAC) Experimentation Center (MEC) developed an exercise called Double Jeopardy as a rehearsal for a United States-Philippines BALIKATAN 2012 exercise. The MEC invited NPS HFN center personnel

with their ICT equipment to participate in both exercises in support of humanitarian assistance/disaster relief (HA/DR) scenarios. The NPS HFN team was integrated by:

- Brian Steckler: NPS Faculty and HFN Center Director.

- Christian Gutierrez, Mark Simmons, and Marcelo Perfetti: NPS students.

Other participants were the organizing institution (MEC team) and cellular technicians from MONAX Lockheed Martin. The exercise took place at the U.S. Marine Corps Base in Kaneohe Bay, Hawaii.

The primary goal of the exercise was to integrate COTS and MONAX technologies in order to put together a successful product during BALIKATAN 12. The exercise was structured in two phases. The first phase consisted of the installation of one MONAX node at a Radar Road site and linking this to the MEC lab through a WiMAX link to get Internet VSAT service. During this phase, Internet access was changed to BGAN Internet service (the service available in the Philippines). In the second phase, an additional MONAX node was installed at Retrans Hill and was linked to the first node through another WiMAX link. After the system was working, coverage area and data throughput was measured to analyze system performance.
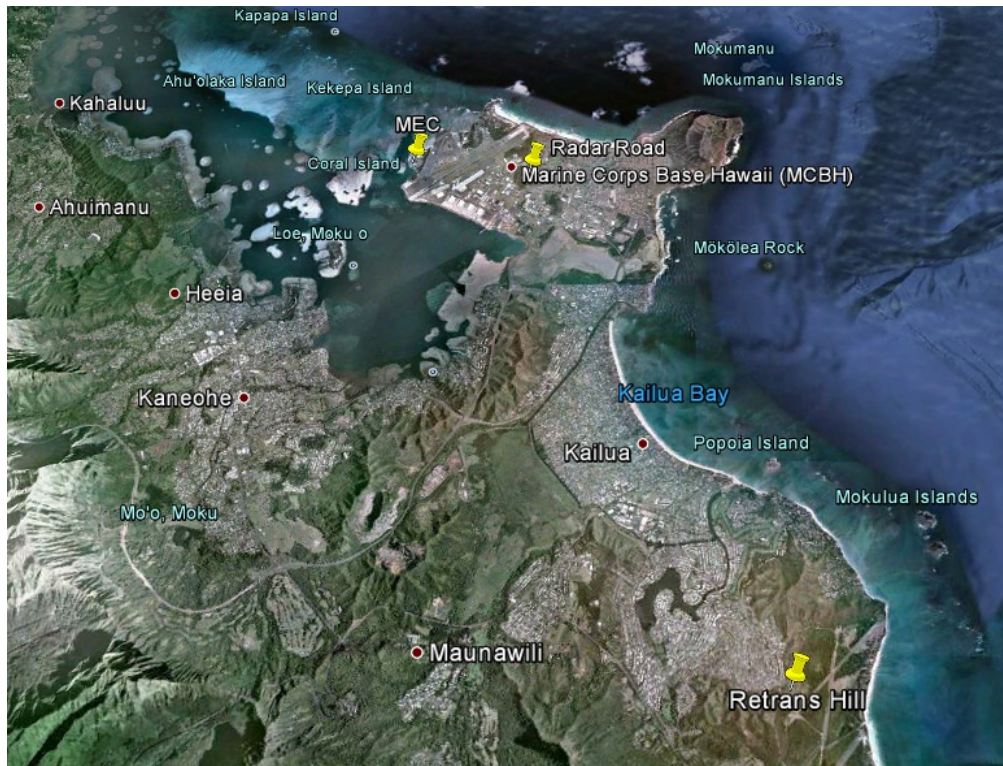
Figure 42.   Double Jeopardy Sites location

This was a very realistic HA/DR scenario for the NPS HFN group. First, the team traveled by commercial airline with all of its equipment. This condition limited the amount of HFN equipment that could be carried. Commercial airlines limited the weight of luggage to 70 pounds at no extra charge and up to 100 pounds for $200 per piece. The team carried seven transit cases (Pelican Models 1610, 1650, and 1660) plus one golf bag for four bicycle tripods, and all pieces were under 70 pounds but one (the team was charged $200 on the return flight for that one). It was found than the big model 1660 Pelican cases are more than 30 pounds themselves, so they are not recommended for use with anything except big fragile gear. No generator or alternative power supply system was carried for this exercise. Second, the team carried brand new equipment (BGAN) that could not be tested before departing from Monterey, since these were received a day before departure. This condition added more tasks to the team effort. Third, the work zone was unknown to the team members and no previous reconnaissance could be done

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before arrival. Nonetheless, as a result of these three conditions, the team could explore and learn more about the HFN in support of HA/DR operations in a realistic scenario.

The main requirements for the NPS HFN team were to install BGANs at the Radar Road and Retrans Hill sites for Internet satellite reachback support and a WiMAX link between the Radar Road site and the Retrans Site. In addition, the team planned to collaborate with cellular MONAX installations and field experiments. The WiMAX link between the MEC lab (Building 1386) and the Radar Road site was installed by the MEC team before the NPS HFN team arrived in the operation zone. Figure 43 shows the general schema of the integrated system.
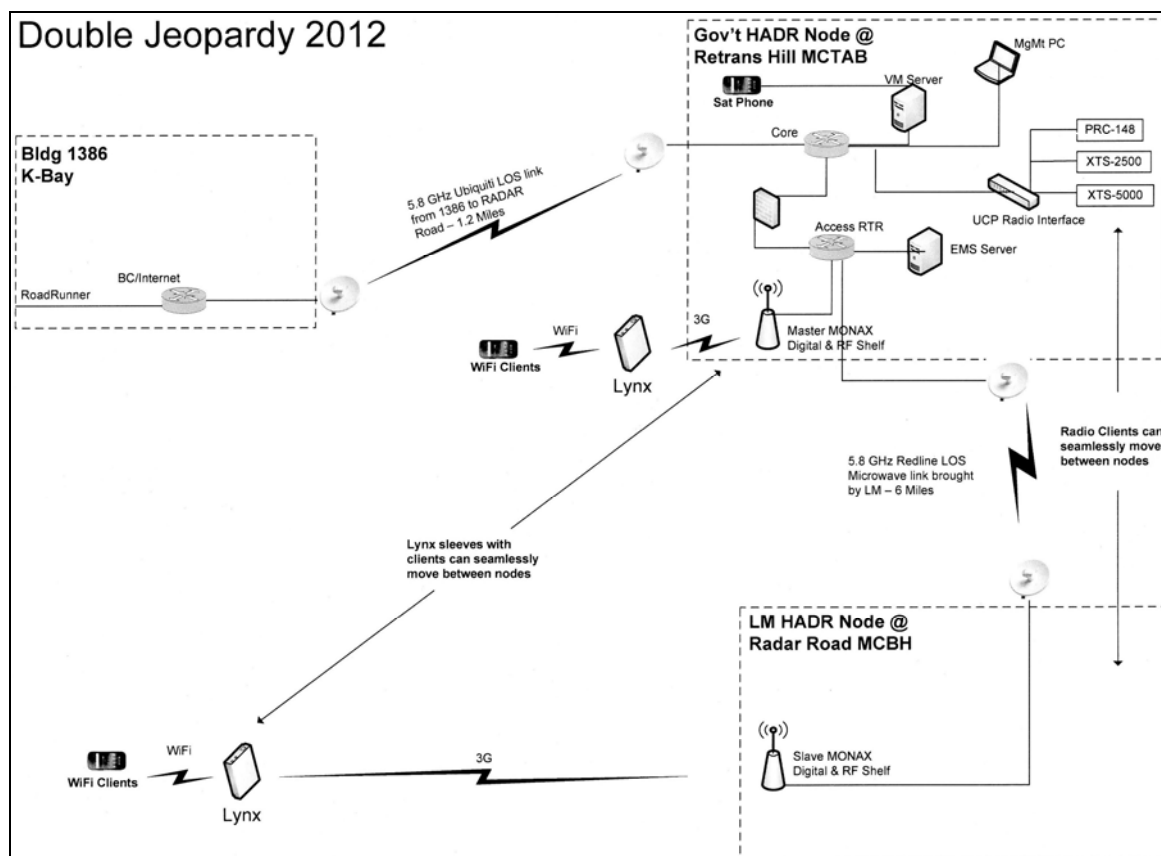
Figure 43.   Double Jeopardy 2012 – general schema (From Stokka, 2012)

2.   Experiment Results

During this exercise, the NPS HFN team worked with InmarSat BGAN equipment and Red Line WiMAX links and collaborated in the installation and operation of a cellular MONAX system.

a.   BGAN

The first system to be installed and tested was the Hughes 9450 BGAN On-the-Move. As mentioned before, this was brand-new, completely unused equipment. The team found two problems: the lack of a magnetic mounting kit and an old firmware version that did not support Windows 7 OS. Exchanging pieces from an old Harris On-the-Move model and screws from other mounting kits, the team solved the first problem easily and the external unit was installed on the roof of a rented SUV. The second issue was more complicated and time consuming. With the old firmware version (5.7.0.6), the unit could not be configured with a Windows 7 Operation System. The team got reachback support from Hughes technical support, who clarified the problem and provided a solution. Fortunately, the team had one laptop with the necessary Windows XP Operation System required to upgrade the firmware to 5.7.0.7.

After installation and configuration, the Hughes 9450 provided very useful Internet access. At the beginning, only one laptop was connected wirelessly to the unit to get Internet Access, since the built-in access point did not work properly. When this problem was solved (explained later in this chapter), this unit showed reliable performance.

The second BGAN used was a brand new Hughes 9202. This small unit had problems with internal batteries (manufacturer supplied) and had to be used with an external power supply (110 Volts). This unit also exhibited problems with its wireless access point, so it had to be used wired.

The third unit installed in support of the Radar Road site was the Thrane & Thrane Explorer 700. Since this is from a different maker, the team had troubles getting into the GUI (due to lack of familiarity with the GUI) and configuring the unit. After configuration and installation, a speed test was developed to check performance with an

on-line application provided by www.speedtest.com. The service showed approximately 350 Kbps (downstream) and 150 Kbps (upstream). Later, this BGAN was successfully connected to the MONAX cellular system to provide Internet access to mobile users. At this time, the three BGANs were installed at the Radar Road site and had problems with the WiFi AP functionality.

Figure 44.   Hughes 9450 on SUV roof and Hughes 9202 and Explorer 700 in the field.

The 3rd day of the exercise, the team concentrated their efforts on fixing the BGAN WiFi problems. The team checked the Operation Systems, phone calls, data rate, and network configuration, and discovered that troubles were not in the BGAN devices but in the surrounding equipment. After turning off many Lynx units (MONAX WiFi hotspots) that were next to the BGANs, the team found that the BGAN WiFi access points started to work seamlessly. The large number of Lynx Sleeve devices had been interfering with the BGAN WiFi access point, but a reduced number of Lynx devices did not cause any problem. Increasing the distance between the BGANs and Lynx Sleeves may have also solved the problem.

b.   WiMAX

One of the missions that the HFN NPS team had was to link the Radar Road site with the Retrans Hill site with a WiMAX link. This was a 6-mile (10-Km), LOS wideband, point-to-point link between the MONAX Master at the Radar Road and the MONAX Slave at the Retrans Hill stations with HFN NPS WiMAX RedLine Bridges in between on bicycle tripods. To accomplish this task, the group started by configuring

the two WiMAX RedLine Bridges near building 1386 before the morning briefing on the first day. After setting up this proper configuration, the group divided into two teams and traveled to both sites. After arriving at each site, the groups accomplished all tasks quickly and successfully. The weather conditions for this first day were favorable— almost no wind and low humidity. In order to improve the link performance, a narrow pointing was made reaching a throughput of 36 Mbps.
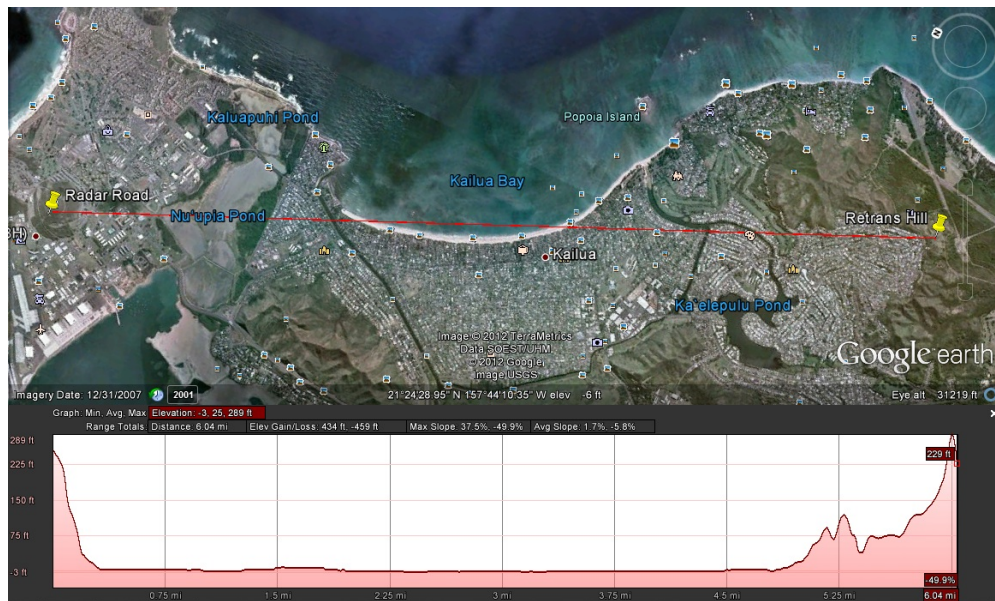
Figure 45.   Radar Rd to Retrans Hill WiMAX Link profile.

On the third day, the weather conditions were slightly different—windy and foggy. This caused trouble in setting up the WiMAX RedLine Link even though they were installed in the same position as on the second day. We had to increase the transmission power for one device from 14 to 25 dBm in order to get the link closed. Since the team was focused on the BGAN WiFi problems, it did not perform a narrow pointing so the throughput link was only 6 Mbps (approximately). In addition, the bicycle tripods used at the top increased oscillations generated by the wind, degrading the throughput.

Figure 46.   WiMAX installation on bicycle tripods

c.   MONAX

MARFORPAC MEC designed this exercise to test the features of the MONAX Cellular system with Lockheed Martin support. At the same time, NPS HFN personnel collaborated and were introduced to this new technology to support HA/DR operations. The experiments were led by Peter Stokka from the MEC, who also collected data gathered from them. Figure 47 shows the expected coverage area for the MONAX Master Slave configuration (estimated by the Lockheed Martin Team).
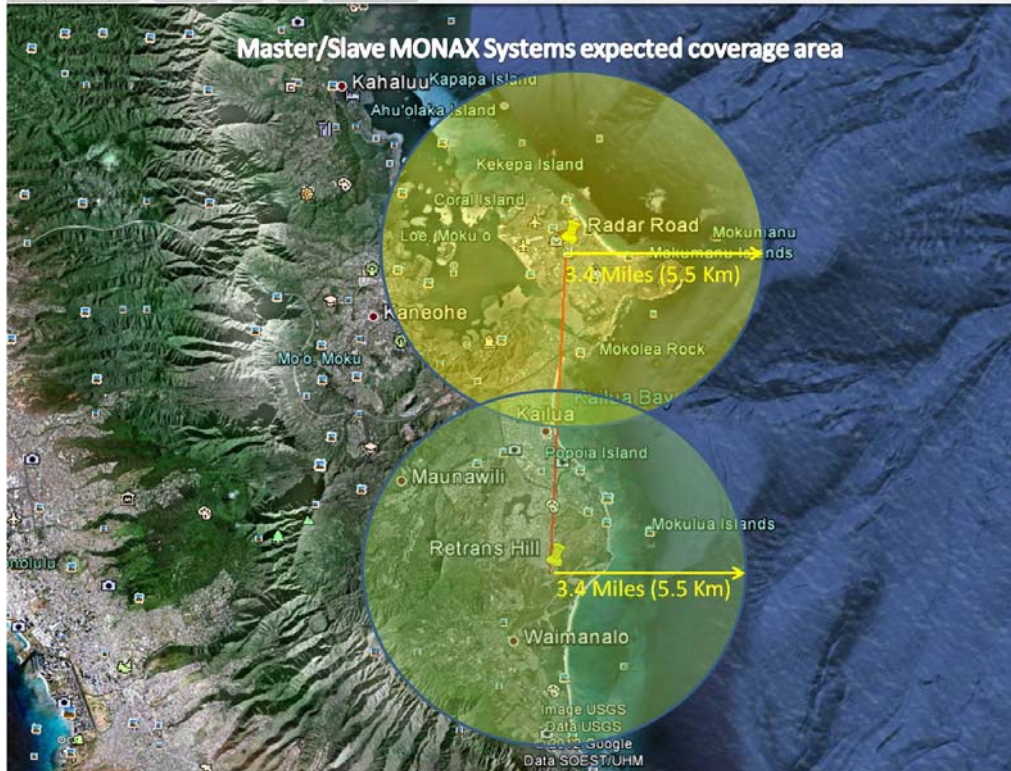
Figure 47.   Estimated MONAX Master/Slave configuration coverage area (From Stokka, 2012)

The first assessment conducted from this MONAX Master/slave configuration involved the configuration of four Android Smart Phones on a single Lynx sleeve connected to the MONAX Master station for a throughput test. This experiment reported an average throughput of 8.7 Mbps. Another experiment of two Android Phones on a single Lynx sleeve connected to the MONAX slave station at Retrans Hill reported throughputs of 8.6 Mbps and 1.1 Mbps thereafter. Significant disparity in throughput for the Androids connected to the MONAX Slave station continued throughout the afternoon.

Three vehicles with separate Lynx sleeves and Android devices were used for the second experiment on the following routes:

- Route 1: From Radar Hill down H-3 to Kamehameha Highway, then following Kalanianaole Highway to Retrans Hill.

- Route 2: From Radar Hill to Mokapu Blvd., then following N. Kalaheo Dr. to Kailua Beach Park.
- Route 3: From Radar Hill to Kaneohe Bay Drive, then along Kamehameha Highway to the Kaneohe Bay Mall.

Distances of 1.5 miles to 4 miles were successfully covered by the MONAX Master/slave configuration. Figure 48 shows the data gathered from Routes 2 and 3 on their way through the assigned routes.
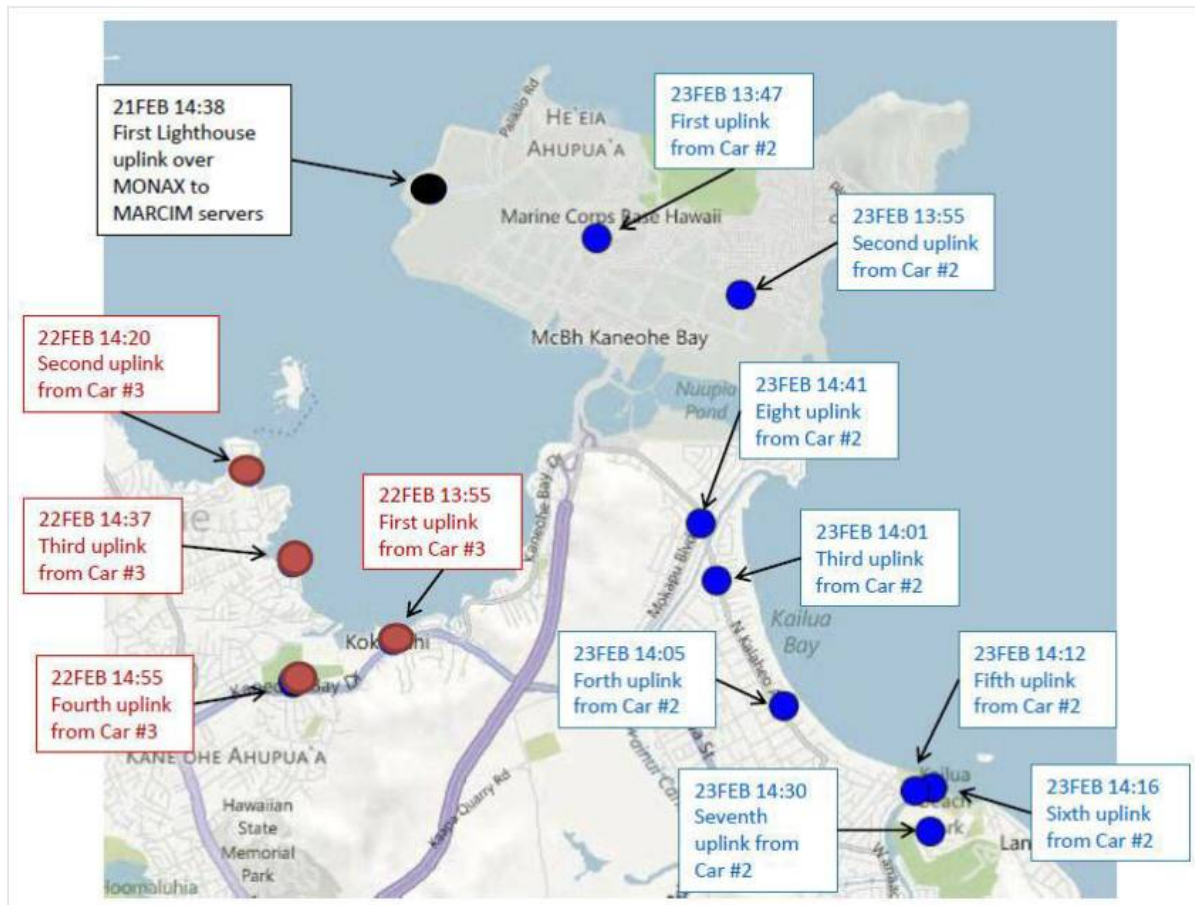
Figure 48.   Check points for Routes 2 and 3 (From Stokka, 2012).

The vehicles did not constantly connect along the routes until the Lynx sleeves switched over between MONAX systems. The handoff was seamless and required no user intervention. After the vehicles returned to Radar Rd. and began to retrograde at the

Retrans Hill site, the MONAX Master system switched to a BGAN connection for Internet reach back. This NPS- established link provided a lower bandwidth but a fully useable connection to the Android devices through the MONAX system (Stokka, 2012).

The NPS team at Retrans Hill connected their personal phones to a Lynx sleeve and walked all around this MONAX Slave site, checking the quality of the connectivity from a variety of places. They tested in heavy foliage and urban environments. The system maintained solid connectivity and never dropped connection, even inside buildings. Overall, it was a positive result (Gutierrez, 2012).

The MONAX site required at least five people to install the mast and antennas. It was provided with a light, manual telescopic mast that supported the two antennas (one for transmission and one for reception) required for operation. It also required a vehicle for transport and shelter, and a generator for power supply. Its units are heavier than the 100 pounds allowed by commercial airlines so must be shipped commercially or via military airlift.

Figure 49.   MONAX Radar Rd and Retrans Hill sites

C.   EXPERIMENT THREE, BALIKATAN 12, PHILIPPINES.

1.   General Description

The third experiment took place in Subic Bay (Republic of Philippines) from 14–24 April, 2012. The U.S. Marine Corps Forces, Pacific Experimentation Center (MEC) supported Exercise Balikatan (BK-12) through a Technology Insertions in the Field

Training Exercise (FTX) and Civil Military Operations (CMO). In addition, the MEC organized static displays and demonstrations during the opening ceremony to support Exercise BK-12 objectives. As part of the technology insertion, the MEC conducted assessments on the following technologies: (a) the Humanitarian Expeditionary Logistics Program (HELP) Joint Capability Technology Demonstration (JCTD), (b) water purification technologies, (c) renewable energy, (d) the Marine Civil Information Management System (MARCIMS), (e) High Frequency Doppler RADAR (HFDR), and (f) the Humanitarian Assistance Disaster Relief Command & Control (HADR C&C)/MONAX (Chang, 2012). The MEC's evaluation provided operational user feedback from participating military units and other agencies to the technology developers. The MEC invited the NPS HFN center to participate in the BK-12 exercises with the center's ICT equipment in support of HFDR and HA/DR scenarios. The NPS HFN team was integrated by:

- Brian Steckler: NPS Faculty and HFN Center Director.

- Christian Gutierrez, Mark Simmons, and Marcelo Perfetti: NPS students.

The entire exercise included more than 6050 participants from more than nine countries (the Philippines, United States, Australia, Indonesia, Japan, Malaysia, South Korea, Singapore, and Vietnam), but the Humanitarian Civic Assistance (HCA) component only included 369 participants from the Philippines and the United States (Colonel Costales, Mr DeGuzman, 2012).

The NPS HFN group participated in two different scenarios, one at Manila (HADR C&C with MONAX) and the other at Subic Bay (an HFDR demonstration with the supporting Defense Advanced Research Projects Agency – Unmanned Aircraft

System (DARPA UAS)). The NPS HFN group was divided into two teams — Brian Steckler and Chris Gutierrez at Camp Aguinaldo, and Mark Simmons and Marcelo Perfetti at Subic Bay.

In Manila, the NPS HFN team supported the installation and operation of the MONAX system and provided Internet connectivity through BGAN devices, supporting the Hawaiian Army National Guard (HING) which was conducting Search & Rescue operation at the Mall of Asia.

In Subic Bay, the NPS HFN team supported networking connectivity and provided Internet access to HFDR construction and demonstration integrated with Defense Advance Research Projects Agency- Unmanned Aircraft System (DARPA UAS).

This was a realistic overseas HA/DR scenario for the NPS HFN group. As in the second exercise (Double Jeopardy) the group traveled in commercial airlines with all its equipment. From lesson learned in previous experiences, the group distributed its gear among eight pelican cases and one extra bag with the bike tripods. No single piece of luggage weighed more than 69 pounds, so there were not any problems with extra fees at commercial airlines. In addition, every case was filled with the gear required to accomplish the specific missions at each site. This improved planification avoided trouble and saved time during the exercise. The group did not carry any Model 1660 Pelican cases (since it weighs 30 pounds by itself) as a lesson learned from the second exercise. No fuel generator or alternative power supply system, either, was carried for this exercise. Most of the gear carried this time had been previously tested and configured to avoid delays during operations. Even though the work zone was unknown to the team members, the group was able to make a cartographic reconnaissance of the area where they would work. The weather played an important role for the performance of the group members and equipment, given the high temperatures and humidity in the Philippines at that time of the year. All of these conditions provided unique characteristics to the NPS HFN center to explore and learn more in a realistic scenario about the HFN in support of HA/DR operations.

The main requirements for the NPS HFN team at Manila were to install BGANs at Camp Aguinaldo and other locations were MONAX systems were employed and to support MONAX system installations and operations.

Balikatan 2012
HING

HADR Node @ BK

BGAN terminal supplied by HNG

VM server/VOIP server/ App Server

Internet

US Mil Radio

US Mil Radio

Motorola XTS-5000

Motorola XTS-5000

UCP Radio Interface

MONAX BaseStation

Sites to set up the HADR node in support of the SAR mission throughout BK may include:

1. Camp Aguinaldo
2. Subic Bay
3. Mall of Asia

3G Range – Blocks or miles depending on terrain

WiFi Range

Lynx

20 Lynx sleeves currently on hand. Each sleeve intended for 2 users, but 8 wifi users can be accommodated.

SmartPhone

Supporting a search and rescue mission, the end users will be: HNG; AFP; PH Fire; PH Red Cross;

US Mil Radio

HNG, AFP, PH Fire, PH Red Cross, using Motorola radios can communicate directly with each other via the UCP system. Each radio type is patched into the same talk group in UCP, which enables the comm link.

Motorola XTS-5000

Figure 50.   General schema for HADR C&C MONAX scenarios (From Stokka, 2012)

At Subic Bay, the NPS HFN team installed, operated, maintained, and monitored an IP-based network allowing for the interconnection with the network of the University of Hawaii high-frequency radar demonstration and the DARPA-UAS demonstration to enable the capturing and sharing of information with external organizations.

Figure 51.   Subic Bay sites location (From Stokka, 2012)

A wired network was built at the Operation Center in San Miguel Naval Station to connect all servers, computers, and communication devices required for proper integration and operation. The WiMAX link (Ubiquity) between the Operations Center and Container Site A (HFDR) was monitored during operations hours. In addition, the team collaborated with DARPA UAS personnel with regard to communication systems and system operation. A satellite BGAN link was used to provide Internet access for communications and video streaming. Figure 52 shows the final schema of the integrated system.
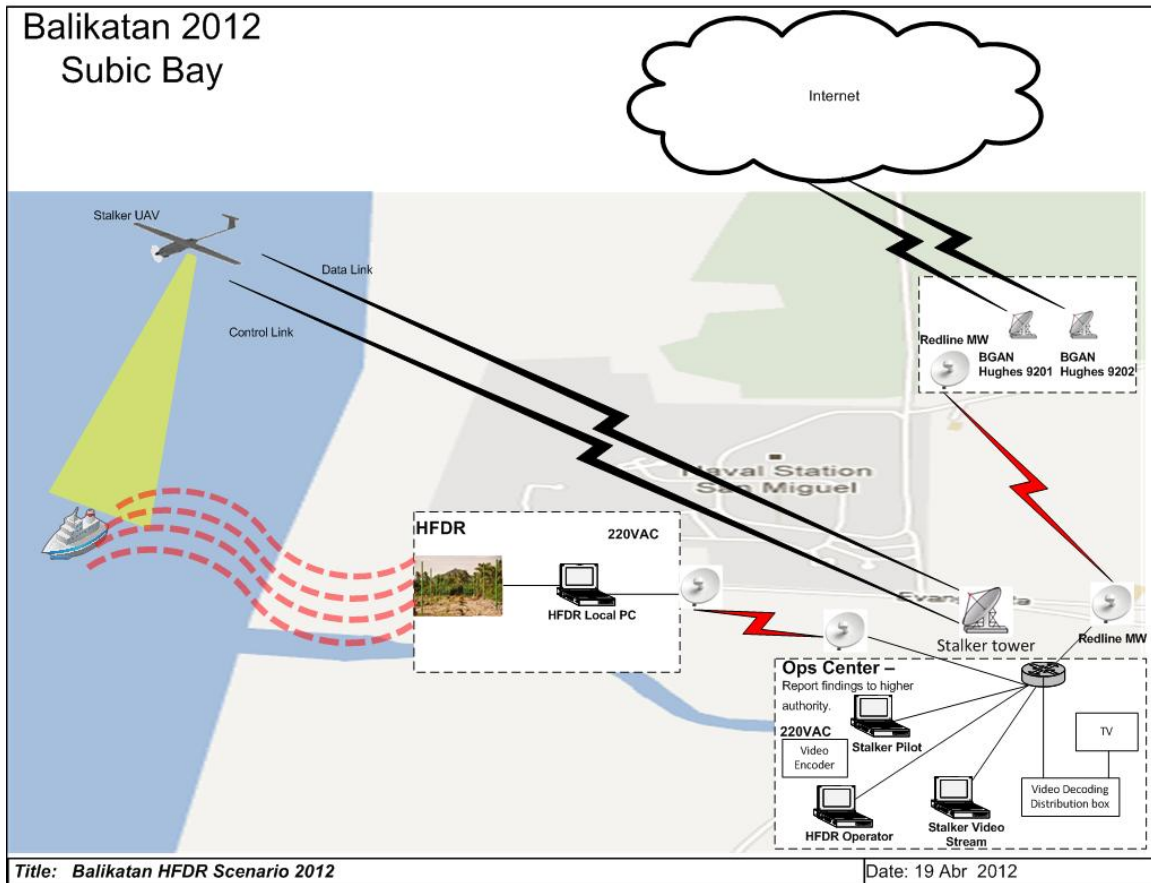
Figure 52.   HFDR/DARPA UAS networking system at Subic Bay (From Stokka, 2012)

The network was monitored using SolarWinds network management software tools. This software provided real time information about network behavior, allowing for the immediate detection of problems in the network.

2.   Experimental Results

During this exercise, the NPS HFN team worked with InmarSat BGAN equipment, Red Line WiMAX links, the Wave Relay WiFi Mesh equipment, and collaborated in the installation and operation of a cellular MONAX system.

a.   *BGAN*

Four BGANs were used during this exercise. The Thrane & Thrane Explorer 700 was assigned to provide Internet reachback access to the HADR C&C

MONAX system in Manila. Even though this was able to provide an X-STREAM data rate of 460 Kbps, it was not continuously employed since there were other VSAT terminals providing more bandwidth in this area.

The second BGAN, which provided an outstanding performance, was the Hughes 9450 On-The-Move. This was continuously used by the NPS HFN team lead in his daily movements from one site to the other, allowing him to maintain control of both teams and provide useful information about the evolution of the exercise. With this BGAN, Skype chat groups was the main application used by NPS team members to communicate with each other and with reachback support technicians from the U.S. Coast Guard in Boston and Hughes Network Systems in California. Using Skype chat groups, the team members could keep records of conversations and use these as part of the consultant documentation.

The other two BGANs (Hughes 9201 and 9202) were assigned to the Subic Bay area. In this area, there was not a VSAT terminal to provide more bandwidth than the BGAN, so the BGAN's performance was crucial for mission success. One unexpected problem appeared when the BGANs were installed on the roof of the Operations Center at San Miguel Naval Station. BGAN's operation frequencies are in the L band (terminal receiving frequencies of 1525.0–1559.0MHz & transmitting frequencies of 1626.5–1660.5MHz), which is close to the DARPA-UAS Video stream frequency (1760 MHz). Even though there was more than a 100 MHz frequency separation, the BGANs may have caused interference to the UAS video stream. Under those circumstances, both systems could apparently not operate at the same time in the same location, so the BGANs needed to be installed at different locations. The BGANs were repositioned in several locations at various distances in an attempt to rule out the BGAN antenna as a possible source of interference. After moving the BGAN antenna 600 meters away and connecting it using Redline AN-80i WiMax devices, the signal interference cleared up. The next day, the BGAN was repositioned 150 meters away from the UAV tracking antenna and no significant signal interference was present. The team having solved this interference, the Hughes 9201 was configured in an X-STREAM mode to uplink the video stream from the UAS to the video web server via the Internet at 460

Mbps. It was also possible to downlink the same video from the Internet server at 460 Mbps. As the whole bandwidth of the Hughes 9201 was dedicated to video streaming, the Hughes 9202 was able to provide broadband Internet access (up to 256 Kbps) for other services in the operation center. In this configuration, the Hughes 9201 and 9202 BGANs allowed the team to accomplish its mission for the rest of the exercise.
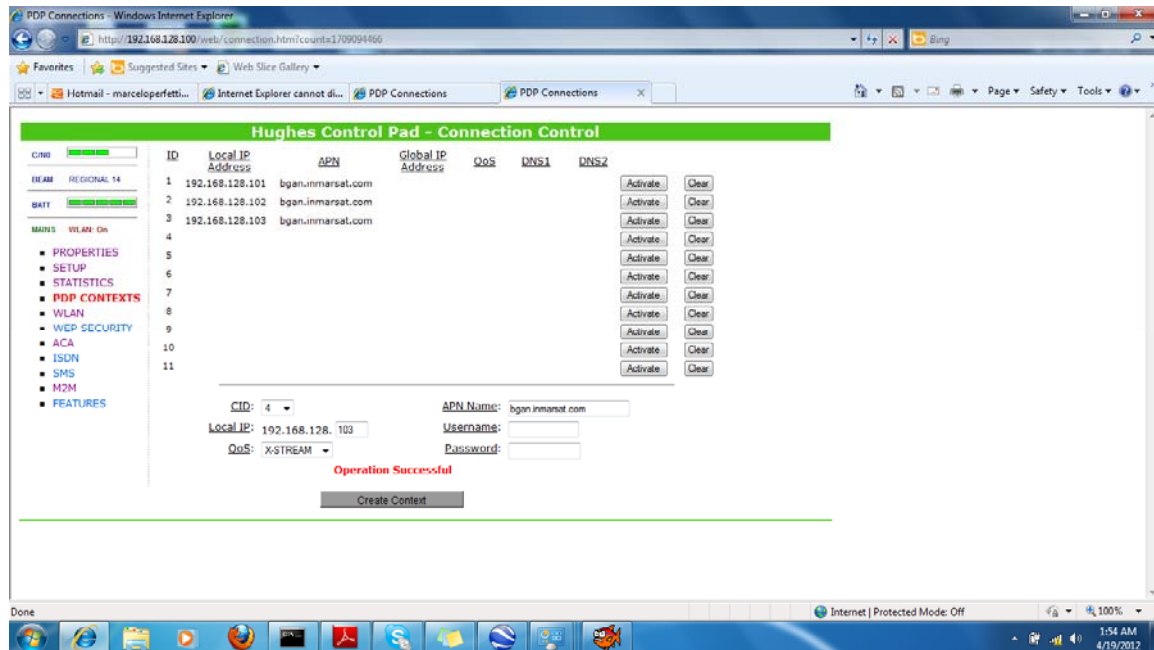
Figure 53.   BGAN Hughes 9201 configuration X-STREAM mode.

In addition, and after further investigation by the team, another source of interference to the DARPA-UAS system was identified. A permanently installed Philippines military high-powered, high-frequency radio station was fewer than 50 meters away from the UAS control antenna. It was found that anytime it transmitted, the HF radio over-powered the downlink signal, interfering with the downlink stream. In conclusion, any transmitter with a frequency at or below 1.7 GHz interferes with the UAS reception frequency. The NPS HFN team recommends that the receptor pass-band filter (or frequency of data-link technology) be redesigned in the UAS Ground Station in order to mitigate further interference and allow other systems to operate simultaneously, since the UAS operators may often have no control over other RF devices in the operation area.

Figure 54.   DARPA UAS video uplink and downlink for Internet video server using
BGAN X-STREAM mode

b.   *WiMAX*

Two WiMAX links were required to support the Subic Bay experiments. The first one had already been installed between the Operations Center and the HFDR by the HFDR team. These WiMAX units linked two points that were at 0.6 miles (1 Km) distance without interruption and at a high bit rate during the entire experiment. The units at the Operations Center were attached to the water tower, one at a height of 36 ft (12 meters) and the other at a height of 8 ft (2.4 meters).

The second WiMAX link was employed to separate the BGANs from the UAS video stream receptor (located at the Operations Center) to avoid the interference described above. In order to accomplish this task, the NPS HFN team experimented with different antenna than the 1-ft-square directional provided. There was no data about how far away the BGAN should be located to avoid interference and, in addition, there were not enough sites to install them safely and close to power sources. A 120° sector antenna would have been a helpful solution that might also have sped up daily installation. First, the remote WiMAX was located at 600 meters from the Operations Center on the roof of the main-gate Guard Post. This remote location worked successfully even though a dense line of trees was in between. Second, it was re-installed with omni directional antennas a

very short distance (100 meters) behind the Philippines Navy Academy Command Post, where it not only worked properly but also did not cause interference.

Figure 55.   WiMAX links with 120° and omni directional antennas in Subic Bay.

The team concluded that sector-and omni-directional antennas are good enough solutions when the links are at short distances and there is not enough time to aim directional antennas.

Figure 56.   WiMAX link with 120° sector antennas on bike tripods.

c.   *WiFi Mesh*

After ensuring data network communication between sites and to the Internet were operating properly, the NPS HFN team at Subic Bay began to experiment with Wave Relay equipment to create a meshed WiFi network that provides alternative network communications. For this experiment, the team used three quad Wave Relay radios with omni directional antennas, Google Earth visualization and Wave Relay GUI.

One quad radio was connected to the VPN router (USCG Mesh WiFi Trident Experimentation Network) and it was connected to the Internet via BGAN. With this configuration, the USCG LT in Boston, and the NPS HFN team lead in Manila could follow and help with their knowledge and expertise to contribute to experiment performance. This node was called WRoIP 19 – NPS in the Google Earth visualization.

The second quad radio was installed on top of the water tower at the Operations Center. This unit was wirelessly linked to the first one with two frequencies (one in 2.4 GHz and the other in 5.8 GHz), and configured as a 0.5 mile link. This node was called Zambales Node 1 in the Google Earth visualization.

The third quad radio was hand held vertically by a Philippine assistant out the window of the team's van. This radio was linked to Node 1 in two frequencies (2.4 and 5.8 GHz). One NPS team researcher sat in the van (which was wire-connected to the quad), and watched the GUI information. This node was called Zambales Node 3 in the Google Earth visualization.

Given this configuration and reachback support, the van began to travel around the base perimeter while observers recorded information, taking screen shots of Google Earth and Wave Relay GUI at 11 test points.
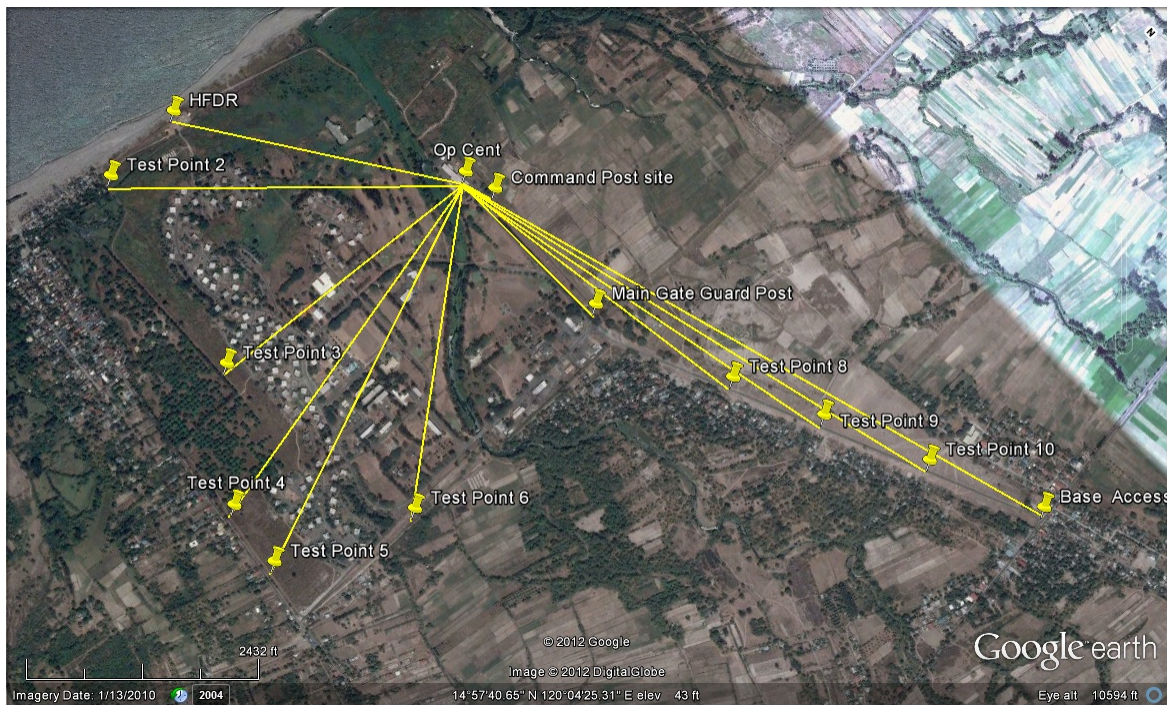
Figure 57.   Van tour around San Miguel Base with test points

Table 7 shows the measurements gathered during this experiment.

#	Location	Distance	LOS	Link Quality
1	HFDR	1000 m (0.62 mile)	Yes	Good
2	Test Point 2	1100 m (0.68 mile)	No	Good
3	Test Point 3	950 m (0.59 mile)	No	Good
4	Test Point 4	1000 m (0.62 mile)	No	Weak
5	Test Point 5	1400 m (0.87 mile)	No	Good
6	Test Point 6	1100 m (0.68 mile)	No	Good
7	Main Gate	600 m (0.37 mile)	No	Strong
8	Test Point 8	1000 m (0.62 mile)	Yes	Good
9	Test Point 9	1400 m (0.87 mile)	Yes	Strong
10	Test Point 10	1700 m (1.06 mile)	Yes	Strong
11	Base Access	2200 m (1.37 mile)	Yes	Strong

Table 7.   Data gathered during the mobile Wave Relay experiment.

The signal quality is specified by a color code that the Wave Relay visualization displays on Google Earth. This is a helpful tool when enhancing a link, since change in color means a better or worse SNR. The scale is thin red, thick red, green, and blue—from the weakest to the strongest SNR available to close a link.

In addition to this tool, the Neighbor SNR page provided by the GUI was also very useful. When the researchers were running the experiment, they continuously watched this information to estimate where they had enough RF energy to close the link between the mobile and the fixed node. Before seeing any color lines on Google Earth, a range of SNR between 5 and 10 dB appeared in the received SNR. That meant that in that

location, a link could possibly be improved by changing the position. The SNR was always better in the 2.4 GHz band than in the 5.8 GHz band.
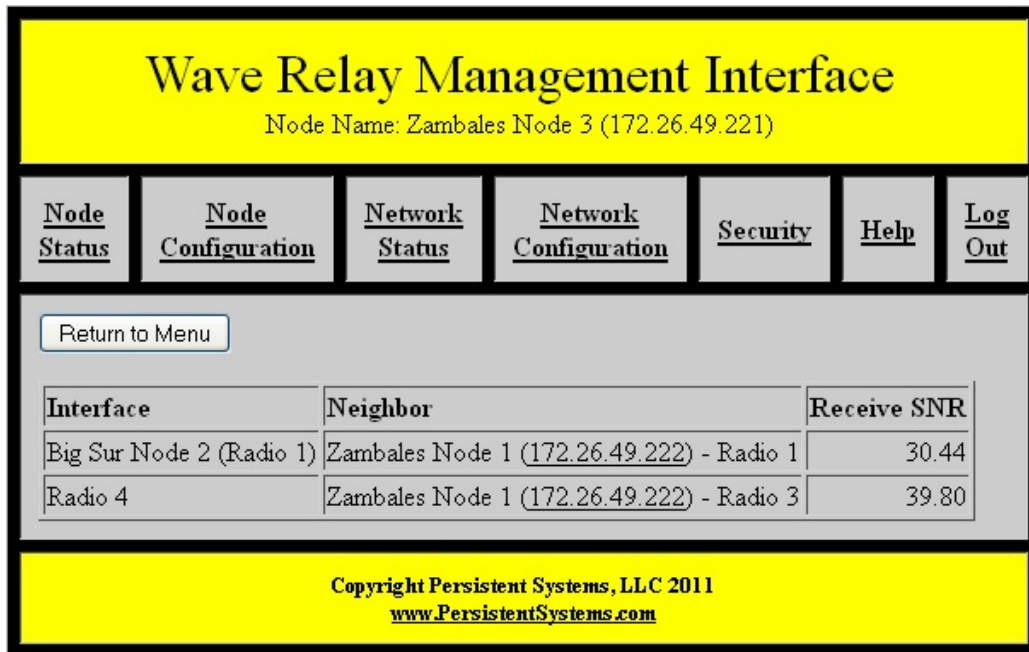
Figure 58.   Neighbor SNR provided by the Wave Relay GUI during experimentation.

The experiment proved that the Wave Relay system was able to replace the whole WiMax infrastructure and also display dynamic, self-healing network configurations without generating any interference to other systems. With this technology, we were also able to track the status of network node locations and signal strengths using Google Earth overlays to create a common operational picture. This COP shot was shared via secure login to parties located in Manila (Philippines), Boston (Massachusetts), New York (New York), and Denver (Colorado).

d.   MONAX

Given the Philippines spectrum regulations, the MONAX system could not be tested completely and was only used indoors during exercises in Manila. Its weight and volume suggest that it should have been shipped a few days before the operators departed.

D. EXPERIMENT FOUR, WAVE RELAY FIELD TEST, SALINAS, CALIFORNIA

1. General Description

The fourth experiment took place in Salinas, California, on May 24, 2012. The HFN center and the Tactical Wireless Research Center developed a field test to evaluate the performance of the quad Wave Relay in a controlled scenario. The experiment team was integrated by:

- Jose Menjivar: NPS Tactical Wireless Research Center student.

- Marcelo Perfetti: NPS HFN center student.

The goal of the experiment was to measure the throughput of a quad Wave Relay in UDP and TCP at four different distances (1, 2, 3, and 4 Kilometers) with LOS, using a freeware software called IPerf.

IPerf is a commonly used network testing tool that can create TCP and UDP data streams and measure the throughput of a network carrying them. For this test, the software was previously installed on two Apple laptops. During the test, 50 samples were taken at each distance and mode (TCP-UDP). The file sample size was 10 Mb, and the packet size 1500 bytes. Figures 59 and 60 shows the configuration used to run the tests.
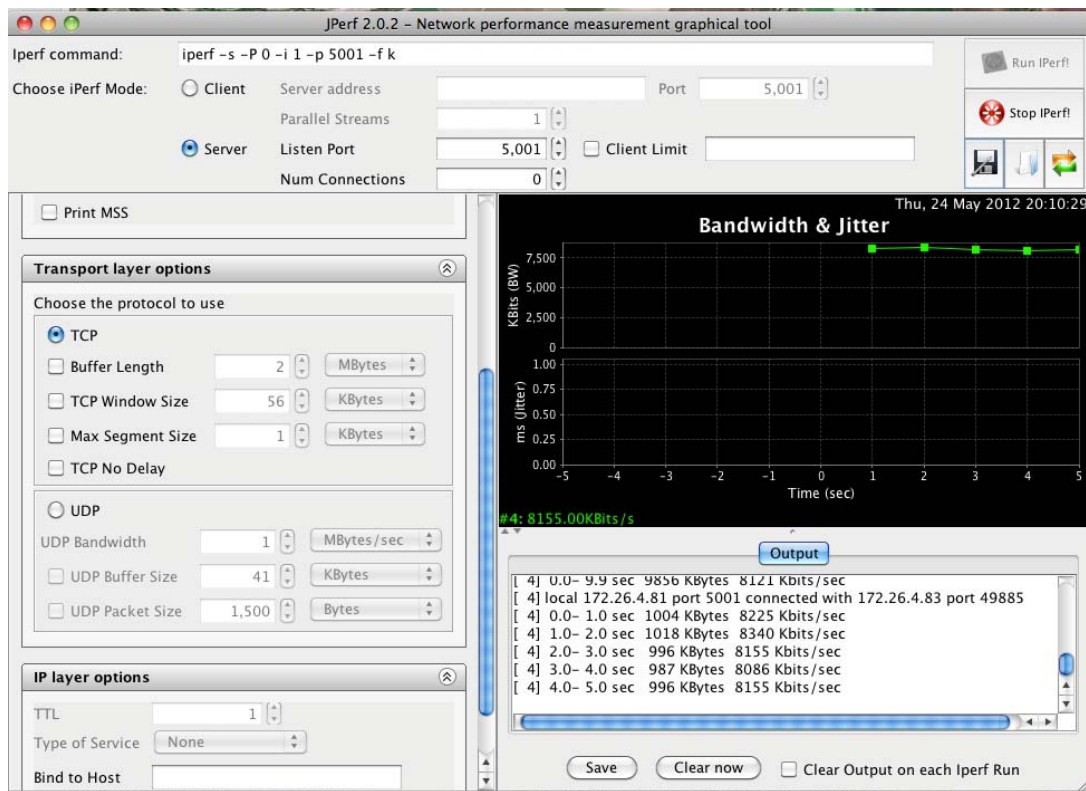
Figure 59.   IPerf configuration for TCP throughput test.
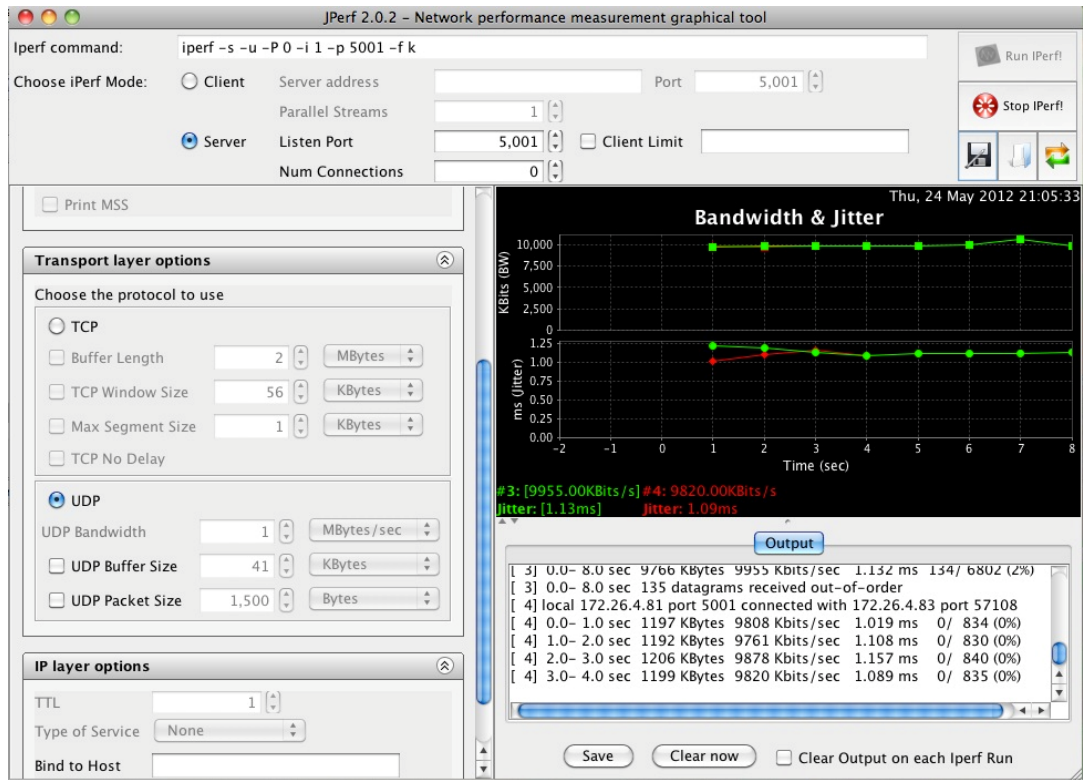
Figure 60.   IPerf configuration for UDP throughput test.

Two Wave Relay quads were employed for this experiment. Of the four radios that each quad has, only two of them were enabled: one at 2.3 GHz (2377 /5–40 MHz) and the other at 5.5 GHz (5500 / 5–20 MHz – Channel 100). They were set at 5 MHz bandwidth and for a 15 mile (24.3 Km) maximum link distance. The antennas used were the Comet SF-5818N-SR for the 5.5 GHz band and the COMET SF245R antennas for the 2.3 GHz band. The quads were powered with COTS car-power inverters.

The experiment was developed in Salinas Valley in order to take advantage of the hills that surround the area and obtain LOS easily. One node (the Fixed node) was installed at 36°33'21.27"N, 121°34'17.26"W, 400 ft (122 meters) altitude and the other (mobile node) at four different locations. Figure 61 shows the locations of each node during the experiment.

Figure 61.　　Site locations of the experiment.

Distances were verified using Google Earth Visualization from the Wave Relay GUI. In order to accomplish this, an Internet service was required. A Hughes 4590 BGAN On-The-Move, used to complete this part of the networking infrastructure, was required for the measurement and recording of experimental data. After completing the initial setup of the experimental system, the mobile node moved to each site to run the throughput test.

Figure 62.　　Wave Relay Fixed-Site installation in Salinas Valley

2. Experiment Results

The environmental test conditions were: temperature of 15° Celsius (60° F), humidity of 40%, wind at 28 Km/h (15 Knots), atmospheric pressure at 1023 hPa, and visibility clear. Table 8 shows the data gathered from fifty samples at each distance and mode during this experiment.

#	Distance	TCP Throughput		UDP Throughput	
		Average	St Dev	Average	St Dev
1	1 Km (0.62 miles)	8.15 Mbps	0.19	8.38 Mbps	2.75
2	2 Km (1.24 miles)	8.25 Mbps	0.03	9.68 Mbps	1.03
3	3 Km (1.86 miles)	8.19 Mbps	0.07	8.57 Mbps	1.71
4	4 Km (2.48 miles)	8.17 Mbps	0.06	9.54 Mbps	1.03

Table 8.   Wave Relay Experiment results

The data shows that the Wave Relay had a very regular performance profile in TCP, from 8.15 to 8.25 Mbps, independent of distance. The standard deviation was also very small and stable. In addition, UDP always performed better than TCP. UDP shows a greater standard deviation than is normal for this protocol behavior where there is no retransmission or flow control and where packets are lost or arrive out of order.

The quad Wave Relays always routed the data through the 2.3 GHz band (out of the two bands programmed in the units), due to its better SNR. The 2.3 GHz band has less free space attenuation (6 dB) than the 5.5 GHz band. Figure 63 shows the 4 Km test with data throughput in each band. To the left of the vertical bar is the throughput on the 2.3GHz band, and to the right, the throughput on the 5.5 GHz band.
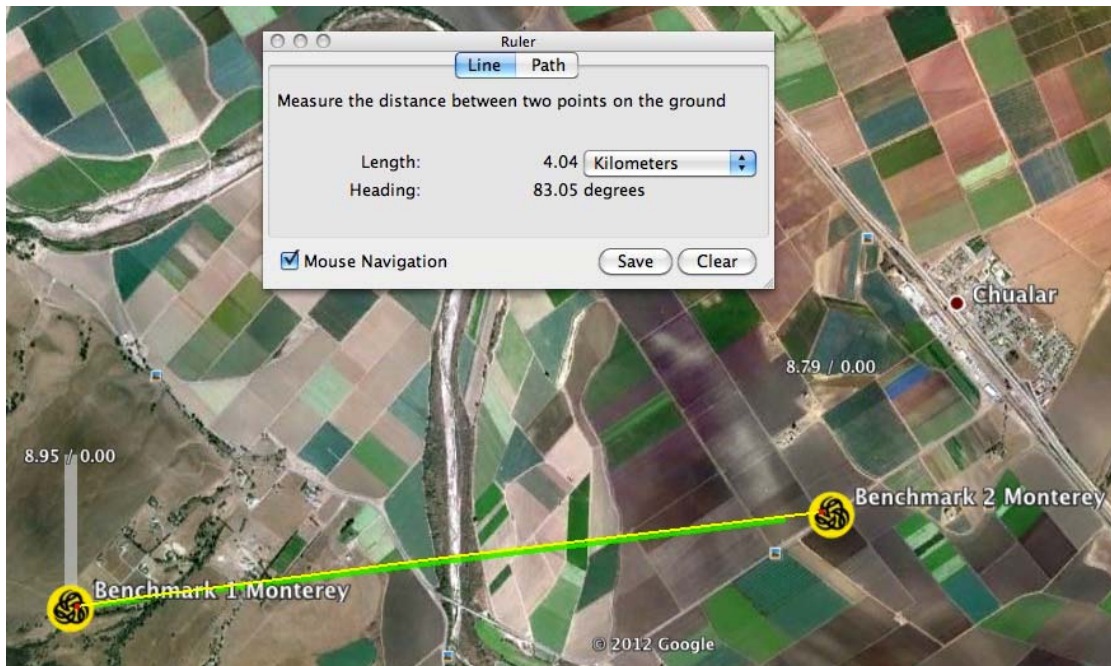
Figure 63.   4 Km test with data throughput information
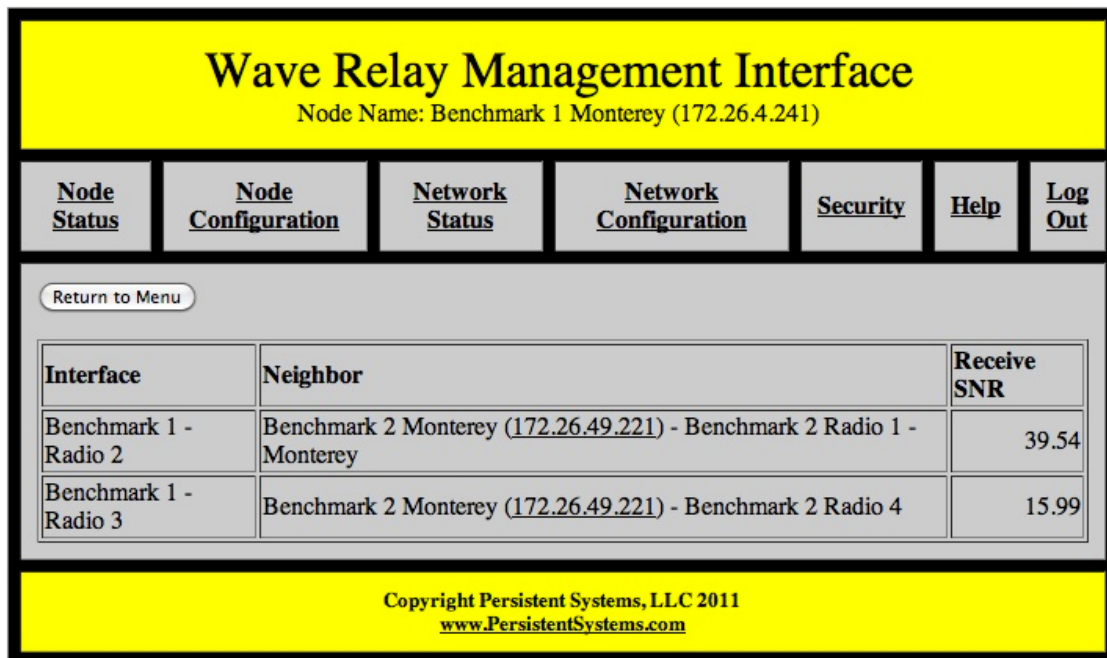
Figure 64.   SNR GUI information for 4 Km tests.

This experiment shows the stable performance of Wave Relays in these conditions, and the data gathered provides a basis for further experiments and research.

E. EXPERIMENT SUMMARIES

1. BGAN

The InmarSat BGAN solutions showed many advantages during the HA/DR experiments. They are suitable for a first responder, given their high portability and built-in battery systems. These are also easy to operate and aim. Their built-in WiFi system also provides fast Internet access. They do not have frequency regulatory problems in any country, since they are globally homologated. The BGANs were able to provide Internet access at data rates from 90 Kbps to 200 Kbps (for up to five users), or 460 Kbps (for video stream to each user). The Table 9 summarizes the throughput performance during the experiments.

Maker	Model	Throughput		Symmetric X-Stream
		Up-link	Down-link	
Hughes	9201	200 Kbps	100 Kbps	460 Kbps
Hughes	9202	150 Kbps	90 Kbps	NA
Hughes	9450	200 Kbps	90 Kbps	NA
Thrane & Thrane	Explorer 700	350 Kbps	150 Kbps	Not tested

Table 9.   BGANs throughput summary

These units are able to provide reasonably good communication services to operation centers during the first days of a disaster, before bigger VSAT terminals arrive at an operation area (MCTC). They can then be deployed further in to inaccessible areas, providing voice, data, and real-time video feed to the Emergency Operation Center. In addition, the BGANs are a reliable backup system, particularly in case there are VSAT troubles.

BGANs have shown that they are an essential part of an HFN solution supporting HADR operations. Even though operational costs may be a concern for information technology managers, the crucial services that they are able to provide in an emergency may justify their cost and usage.

2. WiMAX

The Red Line WiMAX equipment has demonstrated that it is a low cost ($2,000 per node - with two nodes required per link) and easy-to-install data microwave system that can be used to spread the data coverage area during HA/DR operations. Two different configurations where found useful: one for long-range links with directional antennas, and the other for short-range links with sector or omni-directional antennas.

The longest range this solution was tested for was 10 Km (6 miles), with a one-foot-square antenna mounted on bike tripods, the LOS at 36 Mbps. Two main interrelated conditions affect these kinds of links: weather conditions and antenna stability. Wind, dust, and humidity decrease the link throughput and complicate antenna aiming. On the other hand, the antennas have a high wind load (which negatively impacts stability). This issue is worst when the antennas are installed on top of bike tripods. The conclusion is that the lower the antenna, the more stable the link and the better the performance that can be achieved.

When long ranges are not required, omni or sector antennas were found to be an outstanding solution. Short distances of about 600 meters (0.4 miles) could be linked with 120° sector antennas, and distances of 100 meters (328 ft) with omni-directional antennas, both at a high data rate (54 Mbps) and without LOS. This feature speeds up installation and reduces setup time, factors that may be crucial during HADR operations.

Antenna Type	Distance	Throughput	Setup time	LOS
1 ft²	10 Km (6 miles)	6 to 36 Mbps	30 min	Yes
120° Sector	600 meters (0.4 mile)	54 Mbps	15 min	No
Omni Directional	100 meters (328 ft)	54 Mbps	10 min	Yes

Table 10.   WiMAX performance summary

In HA/DR operations, the Red Line WiMAX solution is best suited for long-range links from satellite or terrestrial Internet providers to EOCs, or between different EOCs. Depending on the distance, different sets of antennas can be used to reduce setup times.

The availability of this solution would extend the data-coverage area of MCTC in the Argentine communication systems from a few hundred meters to a few kilometers—depending on LOS availability—at a high-data rate.

3.   WiFi Mesh

The experiments provided valuable information about the communication capabilities of affordable ($6,000) Wave Relay WiFi Mesh equipment. These small and light units provided long range links at high-data-rates, medium-range NLOS links, and an IEEE 801.11g Internet access point.

The Wave Relay system was able to download a real-time video stream from a manned aircraft to a ground station at 10 Km (6 miles) distance with omni-directional antennas. This range could be increased (up to 150 Km) using directional antennas.

During experiment one, the Wave Relay was able to link two NLOS points (at 3.5 Km / 2.2 miles) with omni-directional antennas, whereas WiMAX could not do this with directional antennas. Its GUI and Google Earth visualization provided enough information to find an appropriate site to close the links and support installation.

In addition, the same equipment provided an 802.11g Access Point with roaming service along the mesh. Commercial smart phones and hand-held, WiFi-capable devices were connected to the Internet through Wave Relays during the experiments.

The features of the Wave Relay overlap with WiMAX functionality, so they can be used as WiMAX bridges, and it also provides a dynamic self-healing network configuration. It also performed at an almost constant data rate for links from 1 to 4 Km with LOS.

Type of installation	Antennas	Distance	LOS	Service
Manned Aircraft	Omni	10 Km (6 miles)	Yes	Video stream
Fix on tripods	Omni	3.5 Km (2.2 miles)	No	Google Earth
Fix on tripods	Omni	4 Km (2.48 miles)	Yes	IPerf
Fix to mobile	Omni	2.2 Km (1.37 miles)	Yes	Google Earth
Fix to mobile	Omni	1.4 Km (0.87 miles)	No	Google Earth

Table 11.   Wave Relay performance summary

WiFi mesh Wave Relay has proven to be the more powerful solution to increasing coverage area in HADR operations, with small and light units that can perform as wireless bridges and Internet access points at the same time, and also providing dynamic, self-healing, network configuration and routing. Adding WiFi mesh devices to the Argentine CMTCs in the future would increase the data network coverage area in disaster areas.

4.   MONAX

The Double Jeopardy and BALIKATAN 12 exercises provided important information about the MONAX system. This integrated, 3G, cellular data system provided high data-rate Internet service at 5.5 Km (3.4 miles) from a base station, and has multi-site capability with terminal (sleeves) auto roaming (handoff).

At 700 MHz band, the MONAX system showed better foliage penetration than WiFi equipment. This feature improves the coverage area, especially during HADR operations in forests, but the frequency allocation should be analyzed in every country due to regulatory constraints.

The MONAX system has disadvantages for HA/DR operations where mobility and cost counts. Its high weight makes it inappropriate for commercial airline transportation and requires at least 4 operators for transportation, installation, and operation. But the main drawback of the highly proprietary MONAX system is the acquisition cost for a complete set (two sites configuration) which is around $1,000,000. In addition, each Lynx sleeve costs approximately $1,000 and would be a source of WiFi interference.

This thesis found that the MONAX system is a probable evolution of the Analog Trunking system (the main component of MCTC) or the Digital Trunking APCO P25 radio system (the main component of MCTC-2). A kind of 3/4G cellular system may be the core of the CMTC next generation, where all communication and data services will run over Internet Protocol as commercial 4G cellular solutions (LTE and WiMAX) are defined.

This system is appropriate for the second wave of early responders to a disaster, given the requirements for shelter, transportation, and operators, in the same way that MCTC and MCTC-2 used to work in the Argentine Army. This system may arrive at a disaster zone 48 hours after a disaster and be operational almost immediately.

In order to make this investment rewarding, MONAX requires an Internet bandwidth of 1.5 Mbps or above. In a disaster area, this bandwidth can only be provided by a VSAT system that has the same transportation constraints that the MONAX has now.

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V. CONCLUSIONS

A. RESEARCH FINDINGS

- How will new WiFi COTS Wireless technologies provide larger coverage areas than recent wireless systems?

The Wave Relay Mesh WiFi system has been field tested in three separate experiments, and improvements to the original configuration and architecture in each successive experiment and exercise have shown that in many use cases (such as Hurricane Katrina, Haiti, and the Argentine floods and earthquakes), the integration of mesh WiFi systems into the Argentine Hastily Formed Networks in support of Humanitarian Assistance/Disaster relief missions is both possible and feasible. Performance of the mesh WiFi systems, as currently configured, is exceptional regarding: coverage area, power consumption, easy installation, and dynamic self-healing network configuration. Its exceptional GUI features, such as Google Earth visualization, provided enough information to find an appropriate site to close the links and support installation. Additionally it provides the ability to be device agnostic regarding smart phone devices used to access the IEEE 802.11g access point.

This thesis concludes that the addition of mesh WiFi systems to Argentine HFN in support of HA/DR operations will increase considerably the wireless coverage area. This technology is compatible and complementary to actual systems like the Argentine Mobile Communication Trunking Center (MCTC).

- How will new WiMAX COTS Wireless technologies provide more bandwidth than recent wireless systems?

The Red Line WiMAX Point-To-Point systems have been field tested in three separate experiments, and improvements to the original configuration in each successive experiment and exercise have shown that it is an easy-to-install data microwave system for spreading the data coverage area at high bandwidth (36 Mbps throughput) between sites located up to six miles (10 Km) during HADR operations. Two different

configurations where found useful: one for long-range links with directional antennas and the other for short-range links with sector or omni-directional antennas.

In HA/DR operations, a Red Line WiMAX solution meets the requirement for high bandwidth, since it is most suitable for long-range links from satellite or terrestrial Internet providers to EOCs, or between different EOCs. Depending on distance, different sets of antennas can reduce setup times.

This thesis concludes that the availability of this solution will increase the bandwidth between ICPs or EOCs from different organizations in Argentine HA/DR operations, allowing for more users and real-time video application. This technology is compatible and complementary to actual systems like the Argentine Mobile Communication Trunking Center (MCTC).

- How will new BGAN COTS Satellite equipment provide more throughput than recent satellite systems?

The new BGAN systems have been field tested in four separate experiments and exercises, and improvements to the original configuration in each successive experiment and exercise have shown that it is an easy-to-install and operate Internet satellite solution that provides limited throughput in areas where there is not another VSAT or terrestrial broadband Internet connection (as previously occurred during HA/DR operations).

These units are able to provide reasonably good Internet and WiFi services to small operation centers during the first days of a disaster when no communication infrastructure is in place or the area is inaccessible for bigger satellites terminals. The BGANs can also be deployed further into inaccessible areas, providing voice, data, and real-time video feed with its X-Stream capability to the Emergency Operation Center. In addition, the BGANs are a reliable backup system should the VSAT experience troubles.

This thesis concludes that the addition of BGANs equipments to the actual Argentine HFN centers will provide reasonable throughput in areas where there is not another VSAT or terrestrial broadband Internet connection. This technology is complementary to actual systems like the Argentine Mobile Communication Trunking Center (MCTC), but cannot replace the actual VSAT subsystem that the MCTC has.

- How will new cellular systems provide more coverage area and throughput than recent trunking systems?

The MONAX cellular system has been field tested in two separates exercises and it has shown that it is a complex cellular solution that provides a large coverage area and high throughput in areas where commercial cellular systems are not available (as previously occurred during HA/DR operations). Its large capability should be complemented with VSAT Internet access to improve its performance.

The MONAX system has disadvantages for HA/DR operations, where mobility and cost counts. Its high weight makes it inappropriate for commercial airline transportation and it requires at least four operators for transportation, installation, and operation. The main drawback of the highly proprietary MONAX system is the acquisition cost for a complete set (a two site configuration) which is around $1,000,000. In addition, each Lynx sleeve costs approximately $1,000 and would be a source of WiFi interference.

The MONAX system is a technology evolution of the Analog Trunking system (the main component of Argentine MCTC) and of the Digital Trunking APCO P25 radio system (the main component of MCTC-2). A new 3/4G cellular system will be the core of the CMTC next generation, where all communication and data services will run over Internet Protocol as commercial 4G cellular solutions (LTE and WiMAX) are defined.

This thesis concludes that the replacement of Analog or Digital Trunking subsystems of Argentine Mobile Communication Trunking Centers (MCTC) with new affordable 3/4G new cellular systems will provide more coverage area and throughput to Argentine HA/DR operations. This technology is the evolution of Trunking systems and replaces the actual APCO P25 Trunking subsystem that the MCTC has.

B. FUTURE RESEARCH

This thesis provides field test data about the capabilities of different technologies (Mesh WiFi, WiMAX P-T-P links, BGAN, and MONAX cellular) in support of HA/DR operations. The continuous technology evolution requires continuous research and field

testing. The results of this thesis will be incorporated with additional results from future experiments, and additional determinations can be made on the applicability of these different technologies.

Work at the NPS HFN center is ongoing, and does not stop with the publication of this thesis. Additional field testing, which will include the portable Wave Relay equipment and InmarSat Ku/Ka systems, will be required in the short term.

One broad area of research for HA/DR operation is alternative power sources for small communication devices such as WiMAX and mesh WiFi. During the experiments, the question arose about how alternative power sources might be used to speed-up the installation and autonomy of HFN. Solar systems, wind generators, hydrogen fuel cells, and kinetic chargers are available solutions that should be tested with the same methodology that this thesis used to explore wireless technologies in support of HA/DR operations. The research should be focused on small, light-weight alternative power sources.

Additionally, future research will allow for the further development and refinement of 4G cellular systems. One hoped-for outcome would be to reduce the size, weight, and cost of a cellular system so that a total system would weight 100 lbs or less, and cost less than $300,000 total per site, allowing it to be transported on commercial airlines and to be affordable for small organizations.

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